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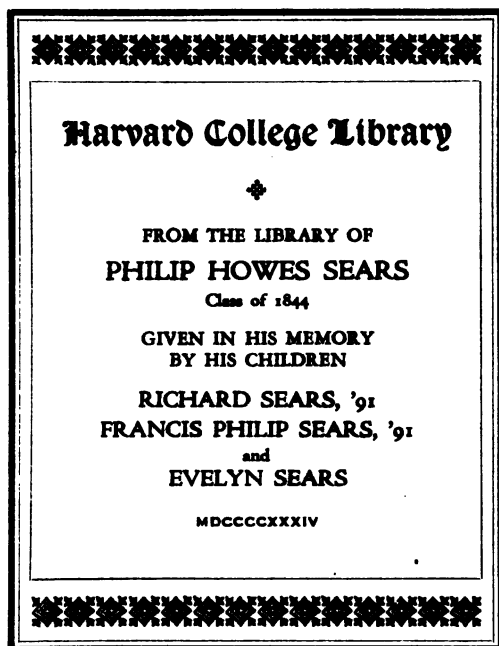
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THE
FIRST THREE SECTIONS

OF

Newton's Principia ;

WITH

COPIOUS NOTES AND ILLUSTRATIONS,

AND

A GREAT VARIETY OF DEDUCTIONS
AND PROBLEMS.

Designed for the Use of Students.

BY THE REV. JOHN CARR, M.A.,

LATE FELLOW OF TRINITY COLLEGE, CAMBRIDGE.

Second Edition,
IMPROVED AND ENLARGED.

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INTRODUCTION.

THE following Compilation was drawn up at a time when the difficulties, which usually present themselves on a first perusal of the Principia, were fresh in the recollection of its Author. Upon a late accidental revision of it he was induced to think that it might, if printed in a convenient form, prove an useful guide to those, who not enjoying the benefits of Academical or other instruction, are yet desirous of becoming acquainted with so much at least of the Principia, as is necessary to a clear comprehension of the more prominent and obvious laws of the Planetary System. Perhaps even to the regularly educated Student it may not be wholly unacceptable as a book of occasional reference; inasmuch as besides the Commentary properly so called, it will be found to contain, carefully arranged under proper heads, all or most of those Problems and Deductions from the Text, which, after having been collected by the Student at the expence of much time and trouble, are usually entered, without any great regard to order or connexion, in the pages of his Manuscript.

The following is the plan and arrangement of this Treatise.

I. Newton's text entire, with the exception of Props. 3, 5, and 17; Lemmas 12, 13, and 14, relating to well-known properties of the Conic Sections; a few of the Scholia; and the

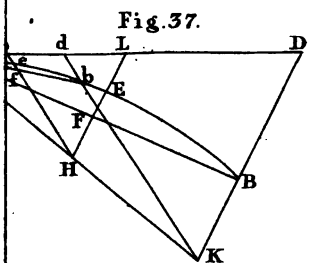
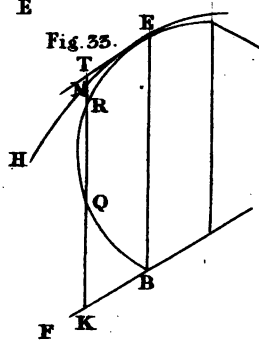
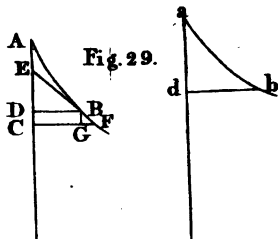
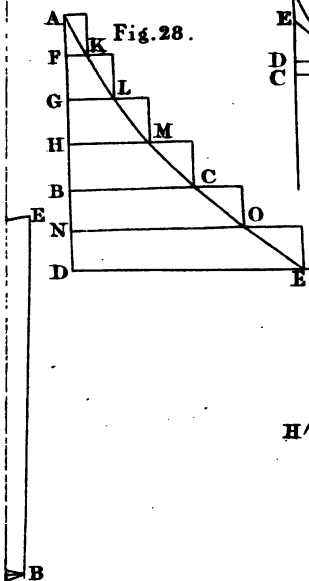
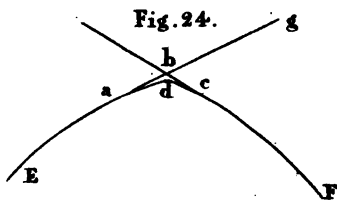
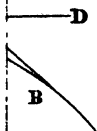
aliter proofs in the 2d and 3d Sections; all of which, as being of less general use and application, might, it was conceived, be omitted without injury to the work.

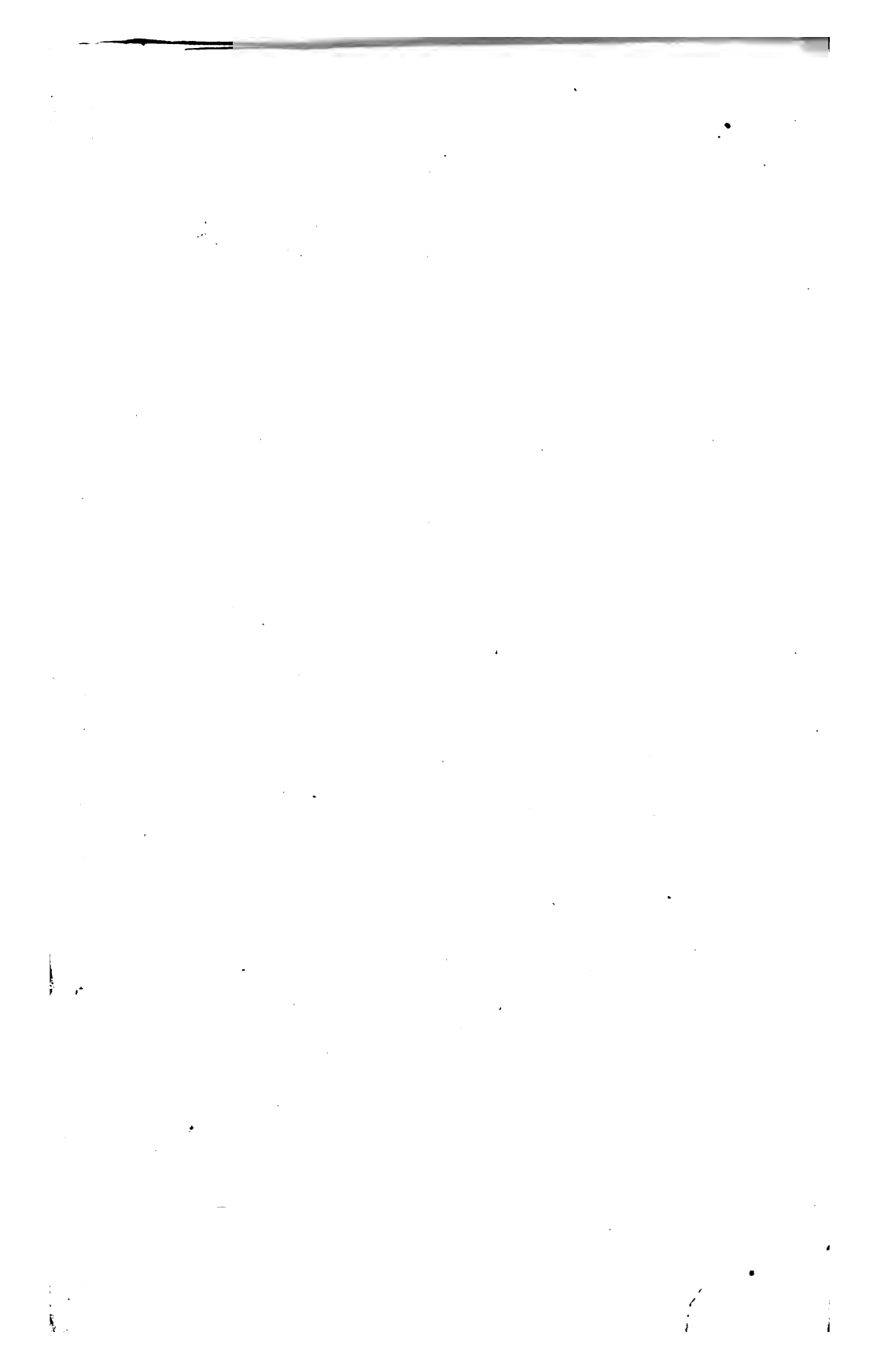
II. A general Introduction to the three Sections, comprising a concise account, with Examples, of the Methods of Exhaustions and Indivisibles, and the doctrine of Limits.

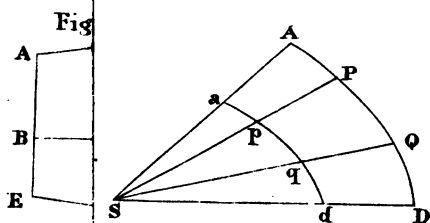
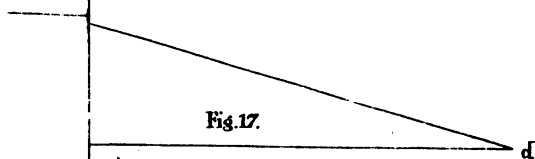
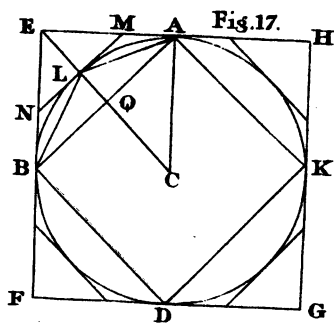
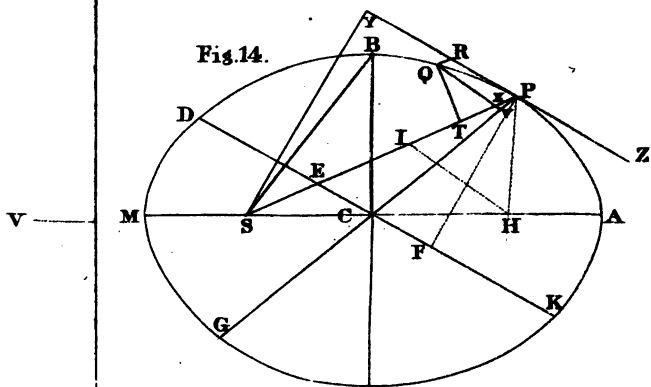
III. Notes explanatory of Newton's text. In this part, which forms the main body of the Treatise, the following method has been invariably adhered to. (*j*) Each Lemma and Proposition is prefaced, wherever the subject appeared to require it, with such introductory remarks as were thought necessary to prepare the reader for Newton's demonstration. (*jj*) The Lemma or Proposition itself, where any difficulty occurs, is explained in as distinct and familiar a way as the subject would admit of. (*jjj*) At the end of each will be found subjoined, under the appellation of Notes, such further remarks, deductions, and problems as the Proposition under consideration seemed naturally to suggest.

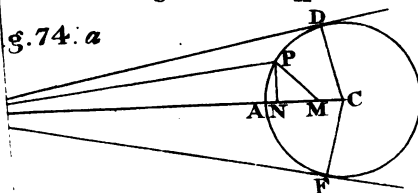
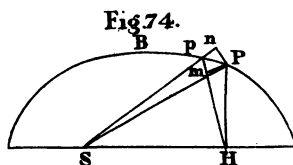
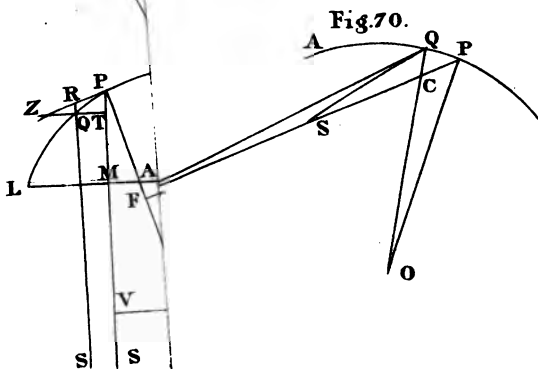
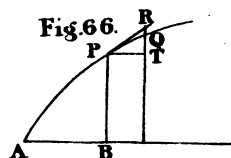
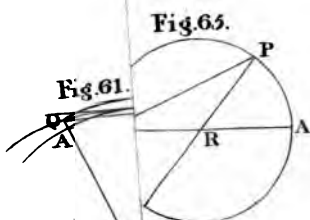
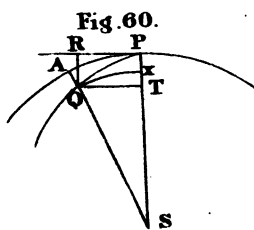
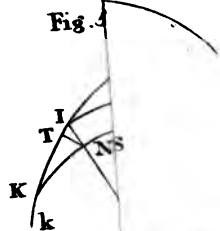
IV. A collection of Miscellaneous Problems, with their solutions.

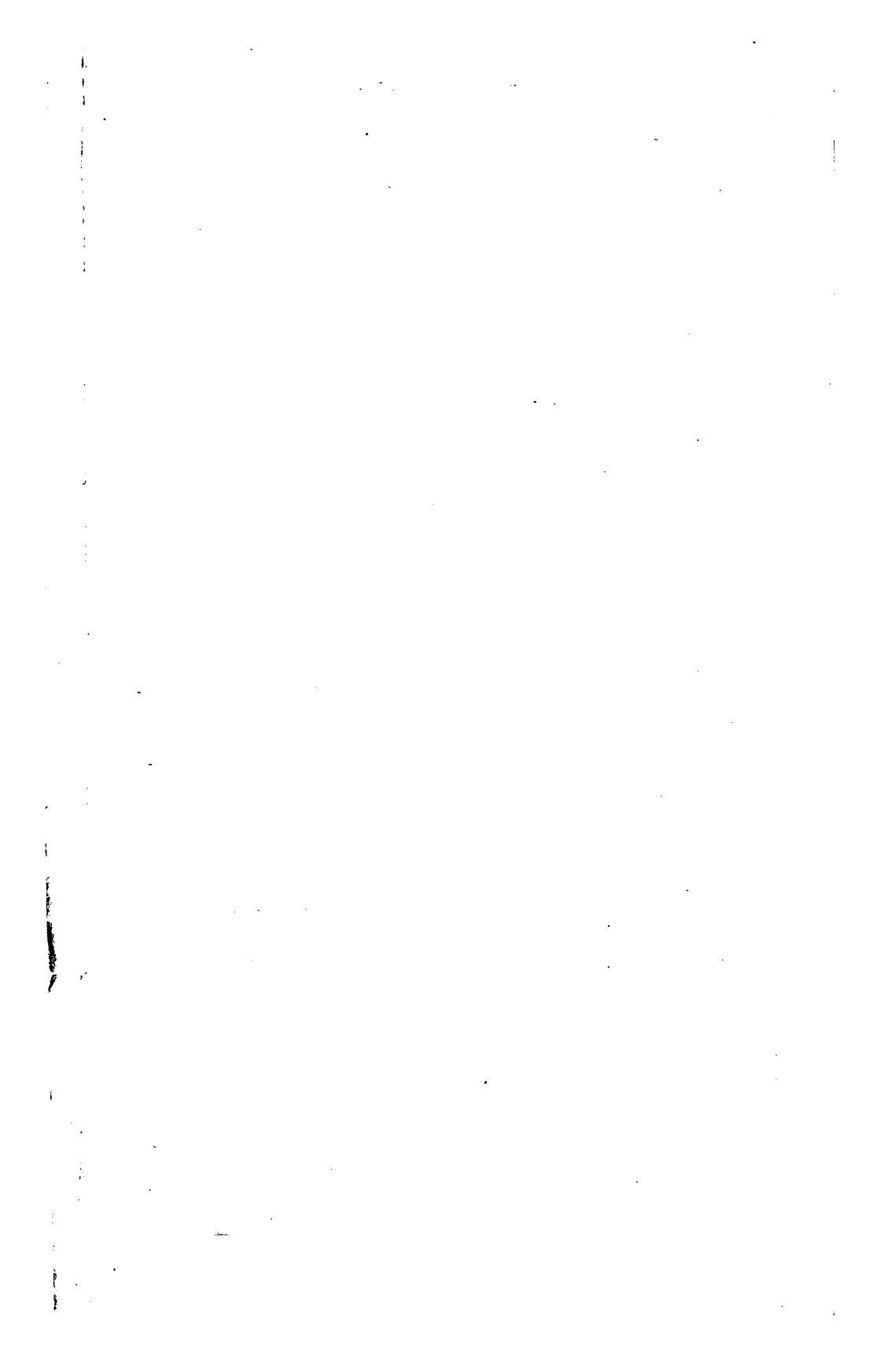
The reader will observe that the short account given of the doctrine of Exhaustions and Indivisibles, and also Arts. 50, 51, and 52, on curvature, have been extracted almost wholly from Maclaurin; and as utility has been his sole object, the Compiler of the following sheets has throughout unreservedly borrowed from every valuable source within his reach.

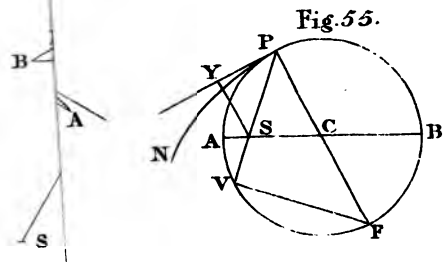
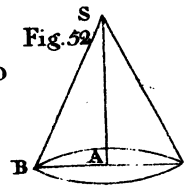
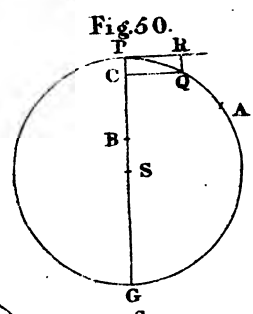
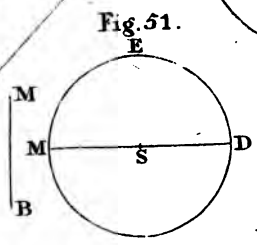
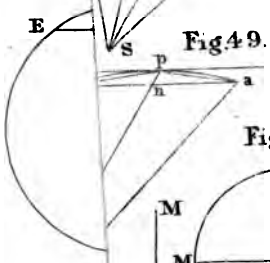
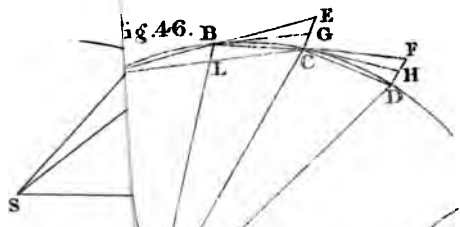
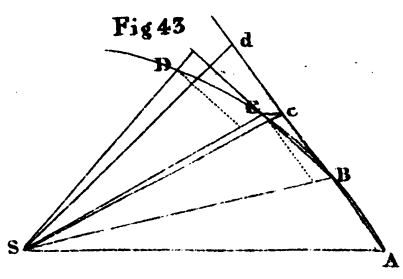
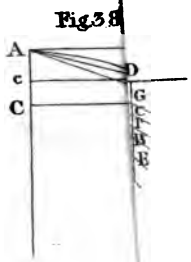


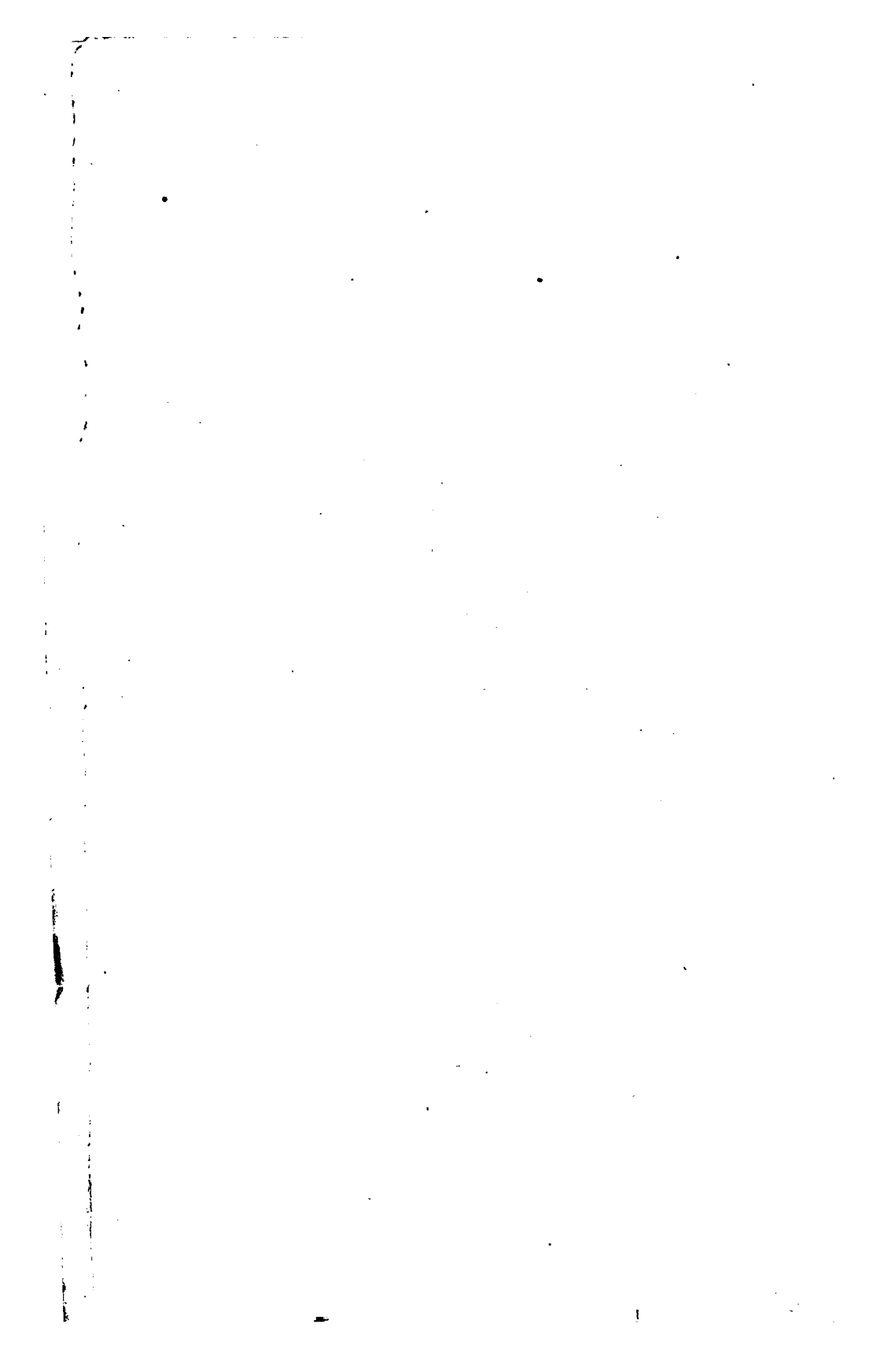


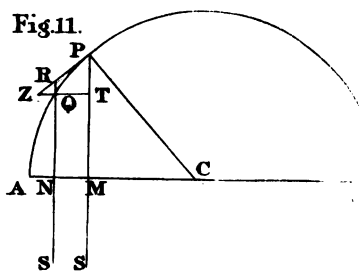
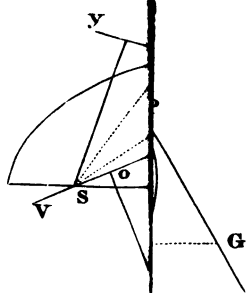
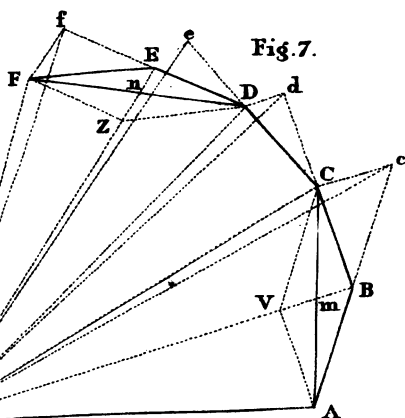
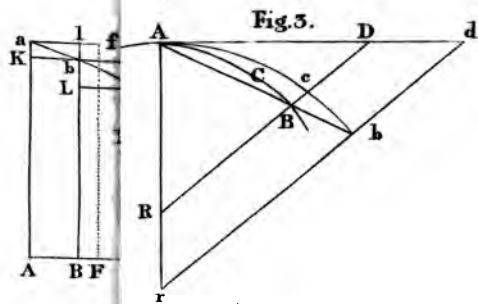


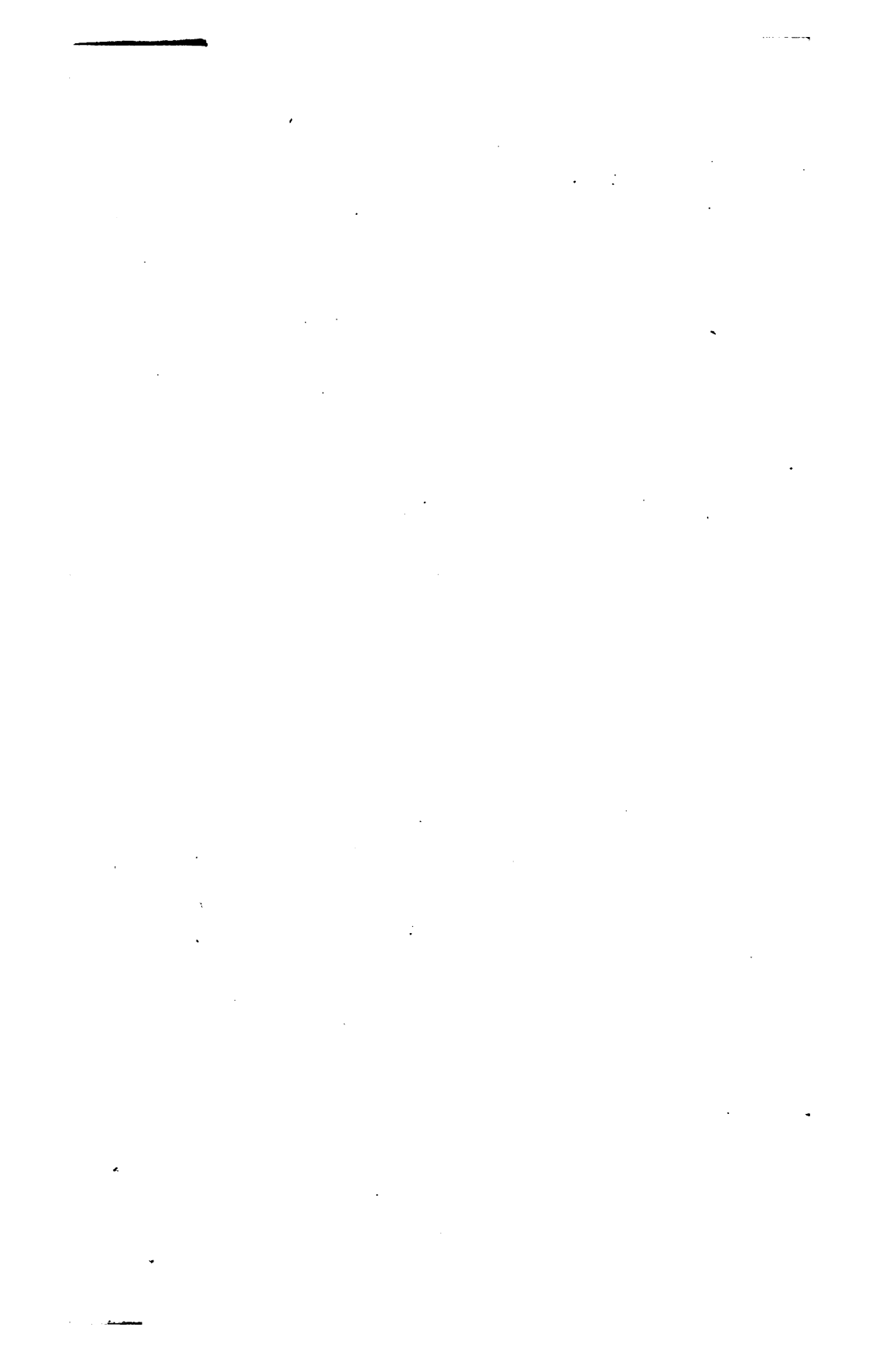


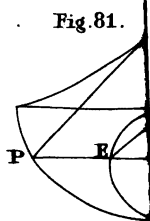
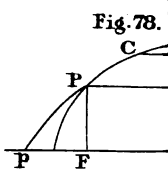
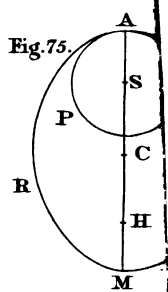












MATHEMATICAL PRINCIPLES

OF

Natural Philosophy.

SECTION I.

OF THE METHOD OF PRIME AND ULTIMATE RATIOS, BY THE HELP OF WHICH THE FOLLOWING PROPOSITIONS ARE DEMONSTRATED.

LEMMA I.

Quantities, and the ratios of quantities, which, in any finite time, tend continually to equality; and, before the end of that time, approach nearer to each other than by any given difference, become ultimately equal.

IF you deny it, let them be ultimately unequal; and let their ultimate difference be D. Therefore they cannot approach nearer to equality than by that given difference D. Which is against the supposition.

LEMMA II.

If in any figure A a c E, terminated by the right lines A a, A E, and the curve a c E, there are inscribed any num-

ber of parallelograms A b, B c, C d, &c. contained under equal bases A B, B C, C D, &c., and the sides B b, C c, D d, &c. parallel to A a, the side of the figure; and the parallelograms a K b l, b L c m, c M d n, &c. are completed. Then, if the breadth of those parallelograms is diminished, and their number is augmented continually; I say, that the ultimate ratios, which the inscribed figure A K b L c M d D, the circumscribed figure A a l b m c n d o E, and the curvilinear figure A a b c d E, have to each other, are ratios of equality.—(Fig. 1.)

For the difference of the inscribed and circumscribed figure is the sum of the parallelograms K l, L m, M n, D o, that is (because of the equality of all their bases,) the rectangle under one of their bases K b, and the sum of their altitudes A a; that is, the rectangle A B l a. But this rectangle, because its breadth A B is diminished indefinitely, becomes less than any given rectangle. Therefore (by Lem. I.) the inscribed and circumscribed, and much more the intermediate curvilinear figure become ultimately equal. Which was to be demonstrated.

LEMMA III.

The same ultimate ratios are also ratios of equality, when the breadths A B, B C, C D, &c. of the parallelograms are unequal, and are all diminished indefinitely.

For let A F be equal to the greatest breadth; and let the parallelogram F A a f be completed. This

will be greater than the difference of the inscribed and circumscribed figures; but, because its breadth $A F$ is diminished indefinitely, it will become less than any given rectangle. Which was to be demonstrated.

Cor. 1. Hence the ultimate sum of the evanescent parallelograms coincides in every part with the curvilinear figure.

Cor. 2. Much more does the rectilinear figure, which is comprehended under the chords of the evanescent arcs $a b, b c, c d$, &c. ultimately coincide with the curvilinear figure.

Cor. 3. As also the circumscribed rectilinear figure, which is comprehended under the tangents of the same arcs.

Cor. 4. And, therefore, these ultimate figures (as to their perimeters $a c E$,) are not rectilinear, but curvilinear limits of rectilinear figures.

LEMMA IV.

If in two figures $A a c E, P p r T$, there are inscribed (as before) two series of parallelograms, an equal number in each; and, their breadths being diminished indefinitely, if the ultimate ratios of the parallelograms in one figure to those in the other, each to each respectively, are the same; I say, that those two figures $A a c E, P p r T$, are to each other in that same ratio.—(Fig. 2.)

For, as the parallelograms in one are severally to

the parallelograms in the other; so, by composition, is the sum of all in one to the sum of all in the other; and so is one figure to the other; because (by Lem. III.) the former figure is to the former sum, and the latter figure to the latter sum, in the ratio of equality. Which was to be demonstrated.

Cor. Hence, if two quantities of any kind are any how divided into an equal number of parts: and those parts, when their number is augmented, and their magnitude diminished indefinitely, have a given ratio to each other, the first to the first, the second to the second, and so on in order; the whole quantities will be, one to the other, in that same given ratio. For, if in the figures of this Lemma, the parallelograms are taken to each other in the ratio of the parts, the sum of the parts will always be, as the sum of the parallelograms; and, therefore, the number of the parallelograms and parts being augmented, and their magnitudes diminished indefinitely, those sums will be in the ultimate ratio of the parallelogram in one figure to the correspondent parallelogram in the other; that is, (by the supposition) in the ultimate ratio of any part of the one quantity to the corresponding part of the other.

LEMMA V.

All homologous sides of similar figures, whether curvilinear or rectilinear, are proportional; and the areas are in the duplicate ratio of the homologous sides.

LEMMA VI.

If any arc A C B, given in position, is subtended by its chord A B, and in any point A, in the middle of a continued curvature, is touched by a right line A D, produced both ways; then, if the points A and B approach one another and meet; I say that the angle B A D, contained between the chord and the tangent, will be diminished indefinitely, and will ultimately vanish.—(Fig. 3.)

For, if that angle does not vanish, the arc A C B will contain with the tangent A D an angle equal to a rectilinear angle; and, therefore, the curvature at the point A will not be continued. Which is against the supposition.

LEMMA VII.

The same things being supposed, I say, that the ultimate ratio of the arc, the chord, and the tangent, to each other, is the ratio of equality.

For, while the point B approaches towards the point A, let A B and A D be considered as produced to the remote points b and d , and let $b d$ be drawn parallel to the secant B D. Let the arc A $c b$ be always similar to the arc A C B. Then, supposing the points A and B to coincide, the angle $d A b$ will vanish, by the preceding Lemma; and, therefore, the right lines A b , A d , which are always finite, and the intermediate arc A $c b$ will coincide, and become

equal among themselves. Wherefore, the right lines $A B$, $A D$, and the intermediate arc $A C B$, which are always proportional to the former, will vanish; and will ultimately acquire the ratio of equality. Which was to be demonstrated.

Cor. 1.—(Fig. 4.) Whence, if through B be drawn $B F$ parallel to the tangent, always cutting any right line $A F$, passing through A , in F ; this line $B F$ will ultimately have the ratio of equality to the evanescent arc $A C B$; because, completing the parallelogram $A F B D$, it always has the ratio of equality to $A D$.

Cor. 2. And, if through B and A more right lines are drawn, as $B E$, $B D$, $A F$, $A G$, cutting the tangent $A D$, and its parallel $B F$; the ultimate ratio of all the abscissæ $A D$, $A E$, $B F$, $B G$, and of the chord, and arc $A B$, to each other, will be the ratio of equality.

Cor. 3. And, therefore, in all our reasonings about ultimate ratios, we may freely use any one of these lines for any other.

LEMMA VIII.

If the right lines $A R$, $B R$, with the arc $A C B$, the chord $A B$, and the tangent $A D$, constitute three triangles $R A B$, $R A C B$, $R A D$, and then the points A and B approach to each other; I say, that the ultimate form of the evanescent triangles is that of similitude, and the ultimate ratio that of equality.—(Fig. 3.)

For, while the point B approaches towards the

point A, consider always A B, A D, A R, as produced to the remote points $b, d,$ and r ; and $r b d$, as drawn parallel to R D; and let the arc A $c b$ be always similar to the arc A C B. And, supposing the points A and B to coincide, the angle $b A d$ will vanish; and, therefore, the three triangles $r A b, r A c b, r A d$, which are always finite, will coincide; and, on that account, become both similar and equal. Therefore the triangles R A B, R A C B, R A D, which are always similar and proportional to these, will ultimately become both similar and equal among themselves. Which was to be demonstrated.

Cor. And hence, in all our reasonings about ultimate ratios, we may indifferently use any one of these triangles for any other.

LEMMA IX.

If a right line A E, and a curve line A B C, given in position, cut each other in a given angle A; and to that right line, in another given angle, B D, C E are ordinately applied, meeting the curve in B, C; and the points B and C together approach towards the point A: I say, that the areas of the triangles A B D, A C E, will ultimately be, one to the other, in the duplicate ratio of the sides.—(Fig. 5.)

For, while the points B, C approach towards the point A, suppose always A D to be produced to the remote points d and e , so that A $d, A e$, may be proportional to A D, A E; and let the ordinates $d b, e c$,

be erected parallel to the ordinates DB , EC , and meeting AB , AC produced in b and c . Let the curve $A b c$ be drawn similar to the curve ABC ; and also the right line Ag , which may touch both curves in A , and cut the ordinates DB , EC , db , ec , in F , G , f , g . Then, supposing the length Ae to remain the same, let the points B and C meet in the point A ; and, the angle cAg vanishing, the curvilinear areas $A b d$, $A c e$, will coincide with the rectilinear areas $A f d$, $A g e$; and, therefore, (by Lem. V.) will be in the duplicate ratio of the sides Ad , Ae . But the areas ABD , ACE , are always proportional to these areas; and the sides AD , AE to these sides. Therefore also, the areas ABD , ACE are ultimately in the duplicate ratio of the sides AD , AE . Which was to be demonstrated.

LEMMA X.

The spaces, which a body describes by any finite force urging it, whether that force is determined and immutable, or is continually augmented or continually diminished, are, in the very beginning of the motion, in the duplicate ratio of the times.

Let the times be represented by the lines AD , AE ; and the velocities generated in those times by the ordinates DB , EC : and the spaces, described with these velocities, will be as the areas ABD , ACE , described by these ordinates; that is, at the very be-

ginning of the motion (by Lem. IX.) in the duplicate ratio of the times A D, A E. Which was to be demonstrated.

Cor. 1. And hence it is easily inferred, that the errors of bodies, describing similar parts of similar figures in proportional times, which are generated by any equal forces, similarly applied to the bodies, and are measured by the distances of the bodies from those places of the similar figures, at which, without the action of those forces, the bodies would have arrived in those proportional times, are nearly in the duplicate ratio of the times in which they are generated.

Cor. 2. But the errors, which are generated by proportional forces, similarly applied, at similar parts of similar figures, are as the forces and the squares of the times jointly.

Cor. 3. The same thing is to be understood of any spaces whatsoever, described by bodies which are urged with different forces. These are, in the very beginning of the motion, as the forces and the squares of the times jointly.

Cor. 4. And, therefore, the forces are as the spaces described in the very beginning of the motion directly, and the squares of the times inversely.

Cor. 5. And the squares of the times are as the spaces described directly, and the forces inversely.

LEMMA XI.

The evanescent subtense of the angle of contact, in all curves, which at the point of contact have a finite curvature, is ultimately in the duplicate ratio of the subtense of the conterminous arc.—(Fig. 6.)

Case 1. Let AB be that arc, AD its tangent, BD the subtense of the angle of contact perpendicular to the tangent, AB the subtense of the arc. Let AG , BG be erected perpendicular to the subtense AB and the tangent AD , meeting in G ; then let the points D , B , G , approach to the points d , b , g ; and let I be the ultimate intersection of the lines BG , AG , supposing the points D , B , to approach continually to A . It is evident, that the distance GI may be less than any assignable. But, (from the nature of circles passing through the points ABG , Abg) $AB^2 = AG \times BD$, and $Ab^2 = Ag \times bd$; and therefore, the ratio of AB^2 to Ab^2 is compounded of the ratios of AG to Ag , and of BD to bd . But, because GI may be assumed less than any assignable length, the ratio of AG to Ag may differ from the ratio of equality, less than by any assignable difference; and, therefore, the ratio of AB^2 to Ab^2 may differ from the ratio of BD to bd , less than by any assignable difference. Therefore, by Lem. I. the ultimate ratio of AB^2 to Ab^2 is the same with the ultimate ratio of BD to bd . Which was to be demonstrated.

Case 2. Let BD be inclined to AD in any given

angle, and the ultimate ratio of BD to bd will always be the same as before; and, therefore, the same as the ratio of AB^2 to Ab^2 . Which was to be demonstrated.

Case 3. And, although the angle D is not given, but the right line BD converges to a given point, or is determined by any other condition whatever; yet the angles D, d , being determined by the same law, will always converge to equality, and approach nearer to each other than by any assigned difference; and by Lem. I. will be ultimately equal; and, therefore, the lines BD, bd are in the same ratio to each other as before. Which was to be demonstrated.

Cor. 1. Therefore, since the tangents AD, Ad , the arcs AB, Ab , and their sines BC, bc , become ultimately equal to the chords AB, Ab ; their squares also will ultimately be as the subtenses BD, bd .

Cor. 2. The same squares are also ultimately as the versed sines of the arcs, which bisect the chords, and converge to a given point. For those versed sines are as the subtenses BD, bd .

Cor. 3. And, therefore, the versed sine is in the duplicate ratio of the time, in which a body describes the arc with a given velocity.

Cor. 4. The rectilinear triangles ADB, Adb are ultimately in the triplicate ratio of the sides AD, Ad ; and in the sesquuplicate ratio of the sides DB, db ; as being in the compound ratio of the sides AD and DB, Ad and db . So also the triangles $ABC,$

$A b c$ are ultimately in the triplicate ratio of the sides $B C, b c$. What I call the sesquiplicate ratio is the subduplicate of the triplicate, which is compounded of the simple and subduplicate ratio.

Cor. 5. And, because $D B, d b$, are ultimately parallel, and in the duplicate ratio of $A D, A d$, the ultimate curvilinear areas $A D B, A d b$ will be (by the nature of the parabola) two-thirds of the rectilinear triangles $A D B, A d b$; and the segments $A B, A b$ will be one-third of the same triangles. And hence these areas, and these segments, will be in the triplicate ratio, as well of the tangents $A D, A d$, as of the chords and arcs $A B, A b$.

SCHOLIUM.

But, we have all along supposed the angle of contact to be neither indefinitely greater, nor indefinitely less, than the angles of contact, which circles contain with their tangents; that is, that the curvature at the point A is neither indefinitely small, nor indefinitely great; or, that the interval $A I$ is of a finite magnitude. For $D B$ may be taken as $A D^3$: in which case, no circle can be drawn through the point A , between the tangent $A D$, and the curve $A B$, and therefore the angle of contact will be indefinitely less than circular angles. And, by a like reasoning, if $D B$ be made successively as $A D^4, A D^5, A D^6, A D^7$, &c. we shall have a series of angles of contact proceeding continually, whereof every succeeding series is indefinitely less than the preceding. And if

DB be made successively as AD^2 , $AD^{\frac{3}{2}}$, $AD^{\frac{4}{3}}$,
 $AD^{\frac{5}{4}}$, $AD^{\frac{6}{5}}$, $AD^{\frac{7}{6}}$, &c. we shall have another se-
 ries of angles of contact, the first of which is of the
 same kind with those of circles, the second indefi-
 nitely greater, and every succeeding one indefinitely
 greater than the preceding. But, between any two
 of these angles, another series of intermediate angles
 of contact may be interposed, proceeding both ways
 indefinitely, whereof every succeeding angle shall be
 indefinitely greater, or indefinitely less than the pre-
 ceding. As if, between the terms AD^2 , and AD^3 ,
 there was interposed the series $AD^{\frac{13}{6}}$, $AD^{\frac{12}{5}}$, $AD^{\frac{9}{4}}$,
 $AD^{\frac{7}{3}}$, $AD^{\frac{5}{2}}$, $AD^{\frac{4}{3}}$, $AD^{\frac{3}{2}}$, $AD^{\frac{12}{5}}$, $AD^{\frac{14}{3}}$, $AD^{\frac{17}{6}}$,
 &c. And again, between any two angles of this se-
 ries, a new series of intermediate angles may be inter-
 posed, differing from one another by intervals inde-
 finitely great. Nor is nature confined to any limit.

Those things, which have been demonstrated of
 curve lines, and the surfaces which they comprehend,
 are easily applied to the curve surfaces and contents
 of solids. But I premised these Lemmas to avoid
 the tediousness of deducing long demonstrations to
 an absurdity, according to the method of the ancient
 geometers. For demonstrations are rendered more
 concise by the method of indivisibles. But, because
 the hypothesis of indivisibles is somewhat harsh, and
 therefore that method is esteemed less geometrical, I
 chose rather to reduce the demonstrations of the fol-
 lowing propositions to the prime and ultimate sums

and ratios of nascent and evanescent quantities; that is, to the limits of those sums and ratios: and so to premise the demonstrations of those limits, as briefly as I could. For hereby the same thing is performed, as by the method of indivisibles; and those principles being demonstrated, we may now use them with more safety. Therefore, if hereafter I shall happen to consider quantities, as made up of particles, or shall use little curve lines for right ones, I would not be understood to mean indivisible, but evanescent divisible quantities; not the sums and ratios of determinate parts, but always the limits of sums and ratios: and, that the force of such demonstrations always depends on the method laid down in the preceding Lemmas.

SECTION II.

OF THE INVENTION OF CENTRIPETAL FORCES.

PROPOSITION I.—THEOREM I.

That the areas, which revolving bodies describe by radii, drawn to an immoveable centre of force, do both lie in the same immoveable planes, and are proportional to the times in which they are described.—(Fig. 7.)

Let the time be divided into equal parts, and in the first part of time, let the body, by its power of persevering in its state of uniform motion in a right line, describe the right line AB . In the second part of time, the same would, if not hindered, proceed directly to c , describing the line Bc equal to AB ; so that by the radii AS , BS , cS , drawn to the centre, the equal areas ASB , $BS c$, would be described. But when the body is arrived at B , let a centripetal force act at once, with a strong impulse, and make the body turn aside from the right line Bc , and afterwards continue its motion along the

right line BC . Draw cC parallel to BS , meeting BC in C ; and, at the end of the second part of time, the body will be found in C , in the same plane with the triangle ASB . Join SC ; and, because SB and Cc are parallel, the triangle $SB C$ will be equal to the triangle $SB c$, and therefore also to the triangle SAB . By a like argument, if the centripetal force acts successively in C, D, E , &c. making the body, in each single particle of time, to describe the several right lines CD, DE, EF , &c. they will lie in the same plane; and the triangle SCD will be equal to the triangle $SB C$, and SDE to SCD , and SEF to SDE . Therefore, in equal times, equal areas are described in one immoveable plane; and, by composition, any sums $SADS, SAFS$, of those areas are to each other, as the times in which they are described. Let the number of those triangles be augmented, and their breadth diminished indefinitely; and (by Cor. 4. Lem. III.) their ultimate perimeter ADF will be a curve line: and therefore the centripetal force, by which the body is perpetually drawn back from the tangent of the curve, will act continually; and any areas described $SADS, SAFS$, which are always proportional to the times of description, will, in this case also, be proportional to those times. Which was to be demonstrated.

Cor. 1. The velocity of a body, attracted towards an immoveable centre in spaces void of resistance, is reciprocally as the perpendicular let fall from that centre on the right line that touches the orbit. For

the velocities in those places A, B, C, D, E, are as the bases AB, BC, CD, DE, EF, of equal triangles; and these bases are reciprocally as the perpendiculars let fall upon them.

Cor. 2. If the chords A B, B C, of two arcs, successively described in equal times by the same body in spaces void of resistance, are completed into a parallelogram A B C V, and the diagonal B V of this parallelogram, in the position which it ultimately acquires, when those arcs are diminished indefinitely, is produced both ways, it will pass through the centre of force.

Cor. 3. If the chords A B, B C, and D E, E F, of arcs, described in equal times in spaces void of resistance, are completed into the parallelograms A B C V, D E F Z; the forces in B and E are to each other in the ultimate ratio of the diagonals B V and E Z, when those arcs are diminished indefinitely. For the motions B C, and E F of the body are compounded of the motions B c, B V, and E f, E Z: but B V and E Z, equal to C c and F f, in the demonstration of this proposition, were generated by the impulses of the centripetal force in B and E, and are therefore proportional to those impulses.

Cor. 4. The forces, by which bodies in spaces void of resistance are drawn back from their rectilinear motions, and turned into curvilinear orbits, are to each other, as those versed sines of arcs described in equal times, which converge to the centre of force, and bisect the chords, when those arcs are diminished

indefinitely. For such versed sines are half the diagonals mentioned in Cor. 3.

Cor. 5. And, therefore, those forces are to the force of gravity, as the said versed sines, to the versed sines perpendicular to the horizon of the parabolic arcs, which projectiles describe in the same time.

Cor. 6. The same things hold good when the planes in which the bodies are moved, together with the centres of force, which are placed in those planes, are not at rest, but move uniformly in a right line.

PROPOSITION II.—THEOREM II.

Every body that moves in any curve line described in a plane, and by a radius drawn to a point, either immoveable, or moving forward with an uniform rectilinear motion, describes about that point areas proportional to the times, is urged by a centripetal force tending to that point.

Case 1. For every body, that moves in a curve line, is turned aside from its rectilinear course by the action of some force that impels it. And that force by which the body is turned off from its rectilinear course, and is made to describe, in equal times, the very small equal triangles SAB , SBC , SCD , &c. about the immoveable point S , acts, in the place B , in the direction of a line parallel to cC ; that is, in the direction of the line BS ; and in the place C , in the direction of a line parallel to dD , that is, in the direction of the line CS , &c. It acts, therefore, al-

ways in the direction of lines tending to that immoveable point S. Which was to be demonstrated.

Case 2. And it is indifferent, whether the surface in which a body describes a curvilinear figure is quiescent; or moves, together with the body, with the figure described, and its point S, uniformly in a right line.

Cor. 1. In spaces or mediums void of resistance, if the areas are not proportional to the times, the forces do not tend to the point in which the radii meet; but deviate therefrom *in consequentia*, or towards the part to which the motion is directed, if the description of areas is accelerated; but *in antecedentia*, if retarded.

Cor. 2. And, even in resisting mediums, if the description of areas is accelerated, the directions of the forces deviate from the concourse of the radii, towards the part to which the motion tends.

SCHOLIUM.

A body may be urged by a centripetal force compounded of several forces. In this case, the meaning of the proposition is, that the force, which is compounded of all, tends to the point S. But, if any force acts perpetually in the direction of lines perpendicular to the described surface, this force will make the body to deviate from the plane of its motion: but it will neither augment nor diminish the quantity of the described surface, and is therefore to be neglected in the composition of forces.

PROPOSITION IV.—THEOREM IV.

That the centripetal forces of bodies, which by an equable motion describe different circles, tend to the centres of the same circles; and are to each other, as the squares of the arcs described in equal times, applied to the radii of the circles.

These forces tend to the centres of the circles, (Prop. II. and Cor. 2. Prop. I.) and are to each other as the versed sines of arcs, described in equal times indefinitely small (by Cor. 4. Prop. I.); that is, as the squares of the same arcs, applied to the diameters of the circles, (by Lem. VII.) and, therefore, since these arcs are as the arcs described in any equal times, and the diameters are as the radii; the forces will be as the squares of any arcs described in the same time, applied to the radii of the circles. Which was to be demonstrated.

Cor. 1. Since those arcs are as the velocities of the bodies, the centripetal forces are in a ratio compounded of the duplicate ratio of the velocities directly, and of the simple ratio of the radii inversely.

Cor. 2. And, since the periodical times are in a ratio compounded of the ratio of the radii directly, and the ratio of the velocities inversely; the centripetal forces are in a ratio compounded of the ratio of the radii directly, and the duplicate ratio of the periodical times inversely.

Cor. 3. Whence it appears, that if the periodical times are equal, and therefore the velocities are as

the radii; the centripetal forces will be also as the radii; and the contrary.

Cor. 4. If the periodical times and the velocities are both in the subduplicate ratio of the radii; the centripetal forces will be equal among themselves; and the contrary.

Cor. 5. If the periodical times are as the radii, and therefore the velocities equal; the centripetal forces will be reciprocally as the radii; and the contrary.

Cor. 6. If the periodical times are in the sesquialtate ratio of the radii, and therefore the velocities reciprocally in the subduplicate ratio of the radii; the centripetal forces will be inversely in the duplicate ratio of the radii; and the contrary.

Cor. 7. And universally, if the periodical time is as any power R^n of the radius R , and therefore the velocity reciprocally as the power R^{n-1} of the radius; the centripetal force will be reciprocally as the power of the radius R^{2n-1} ; and the contrary.

Cor. 8. The same things all follow concerning the times, the velocities, and forces, by which bodies describe the similar parts of any similar figures, that have their centres in a similar position within these figures, by applying the demonstration of the preceding cases to those. And the application is made, by substituting the equable description of areas for equable motion, and using the distances of the bodies from the centres for the radii.

Cor. 9. From the same demonstration it likewise follows, that the arc, which a body, uniformly re-

volving in a circle with a given centripetal force, describes in any time, is a mean proportional between the diameter of the circle; and the space, which the same body, descending by the same given force, would describe in the same given time.

SCHOLIUM.

The case of the sixth corollary is applicable to the celestial bodies (as our countrymen Sir Christopher Wren, Dr. Hooke, and Dr. Halley, have severally observed); and, therefore, in what follows, I intend to treat more at large of those things which relate to a centripetal force decreasing in a duplicate ratio of the distances from the centres.

Moreover, by means of the preceding proposition and its corollaries, we may discover the proportion of a centripetal force to any other known force, such as that of gravity. For if a body, by means of its gravity, revolves in a circle concentric to the earth, this gravity is its centripetal force. But, from the descent of heavy bodies, the time of one entire revolution, as well as the arc described in any given time, is given (by Cor. 9 of this Prop.) And by such propositions, Mr. Huygens, in his excellent book *De Horologio Oscillatorio*, has compared the force of gravity with the centrifugal forces of revolving bodies.

PROPOSITION VI.—THEOREM V.

If a body, in a space void of resistance, revolves in any orbit

about an immoveable centre, and in an indefinitely small time describes any nascent arc; and the versed sine of that arc is supposed to be drawn, which may bisect the chord, and being produced may pass through the centre of force; the centripetal force, in the middle of the arc, will be as the versed sine directly, and the square of the time inversely.

For the versed sine, in a given time, is as the force (by Cor. 4. Prop. I.) and increasing the time in any ratio, because the arc will be increased in the same ratio, the versed sine will be increased in the duplicate of that ratio, (by Cor. 2 and 3, Lem. XI.); and therefore is as the force, and the square of the time. Subduct on both sides the duplicate ratio of the time, and the force will be as the versed sine directly, and the square of the time inversely. Which was to be demonstrated.

And the same thing is also easily demonstrated by Cor. 4. Lem. X.

Cor. 1.—(Fig. 8.) If a body P, revolving about the centre S, describes a curve line A P Q, and a right line Z P R touches that curve in any point P; and, from any other point Q of the curve, Q R is drawn parallel to the distance S P, meeting the tangent in R; and Q T is drawn perpendicular to the distance S P; the centripetal force will be reciprocally as the solid $\frac{S P^2 \times Q T^2}{Q R}$; if the solid is taken

of that magnitude which it ultimately acquires, supposing the points P and Q continually to approach

to each other. For QR is equal to the versed sine of double the arc QP , in whose middle is P : and double the triangle SPQ , or $SP \times QT$ is proportional to the time, in which that double arc is described; and therefore may be used for the exponent of the time.

Cor. 2. By a like reasoning the centripetal force is reciprocally as the solid $\frac{SY^2 \times QP^2}{QR}$; if SY is a perpendicular, let fall from the centre of force on PR , the tangent of the orbit. For the rectangle $SY \times QP$ and $SP \times QT$ are equal.

Cor. 3. If the orbit is either a circle, or touches or cuts a circle concentrically, that is, contains with a circle an indefinitely small angle of contact or section, having the same curvature and the same radius of curvature at the point P ; and if PV is a chord of this circle, drawn from the body through the centre of force; the centripetal force will be reciprocally as the solid $SY^2 \times PV$. For $PV = \frac{QP^2}{QR}$.

Cor. 4. The same things being supposed, the centripetal force is as the square of the velocity directly, and that chord inversely. For the velocity is reciprocally as the perpendicular SY , by *Cor. 1*, *Prop. I*.

Cor. 5. Hence, if any curvilinear figure APQ is given; and therein a point S is also given, to which a centripetal force is perpetually directed; the law of centripetal force may be found, by which the body

P, continually drawn back from a rectilinear course, will be retained in the perimeter of that figure, and will describe the same by a perpetual revolution. That is, we are to find by computation, either the solid $\frac{S P^2 \times Q T^2}{Q R}$, or the solid $S Y^2 \times P V$, reciprocally proportional to this force. Examples of this we shall give in the following Problems.

PROPOSITION VII.—PROBLEM II.

Let a body revolve in the circumference of a circle; it is required to find the law of centripetal force tending to any given point.—(Fig. 9.)

Let $V Q P A$ be the circumference of the circle; S the given point, to which the force tends, as to a centre; P the body moving in the circumference; Q the next place into which it is to move, and $P R Z$ the tangent of the circle at the preceding place. Through the point S let the chord $P V$ be drawn; and, the diameter $V A$ of the circle being drawn, let $A P$ be joined; and let fall $Q T$ perpendicular to $S P$, which produced may meet the tangent $P R$ in Z ; and lastly, through the point Q let $L R$ be drawn, which may be parallel to $S P$, and may both meet the circle in L , and the tangent $P Z$ in R . And, because of the similar triangles $Z Q R$, $Z T P$, $V P A$, $R P^2$, that is $Q R L$ will be to $Q T^2$, as $A V^2$ to

$P V^2$. And, therefore, $\frac{Q R L \times P V^2}{A V^2}$, is equal to

$Q T^2$. Let these equals be multiplied into $\frac{S P^2}{Q R}$, and

the points P and Q continually approaching, for $R L$

write $P V$. Thus we shall find $\frac{S P^2 \times P V^3}{A V^2} =$

$\frac{S P^2 \times Q T^2}{Q R}$. Therefore (by Cor. 1 and 5, Pro-

position VI.) the centripetal force is reciprocally as

$\frac{S P^2 \times P V^3}{A V^2}$; that is (because $A V^2$ is given) recip-

rocally as the square of the distance or altitude $S P$, and the cube of the chord $P V$ jointly. Which was to be found.

Cor. 1. Hence, if the given point S , to which the centripetal force always tends, is placed in the circumference of this circle, suppose at V , the centripetal force will be reciprocally as the quadrato-cube (or fifth power) of the altitude $S P$.

Cor. 2.—(Fig. 10.) The force by which the body P in the circle $A P T V$ revolves about the centre of force S , is to the force by which the same body P may revolve in the same circle, and in the same periodical time, about any other centre of force R , as $R P^2 \times S P$, to the cube of the right line $S G$, which is drawn from the first centre of force S , to the tangent of the orbit $P G$, and is parallel to the distance $P R$ of the body from the second centre of force R .

For, by the construction of this proposition, the former force is to the latter, as $R P^2 \times P T^3$ to $S P^2 \times P V^3$; that is, as $S P \times R P^2$ to $S P^3 \times P V^3$ $\frac{P T^3}{P T^3}$; or (because of the similar triangles $P S G, T P V$) to $S G^3$.

Cor. 3. The force, by which the body P in any orbit revolves about the centre of force S , is to the force, by which the same body P may revolve in the same orbit, and in the same periodical time, about any other centre of force R , as the solid $S P \times R P^2$, contained under the distance of the body from the first centre of force S , and the square of its distance from the second centre of force R , to the cube of the right line $S G$, which is drawn from the first centre of force S to the tangent $P G$ of the orbit, and is parallel to the distance $R P$ of the body from the second centre of force R . For the forces in this orbit, at any point P , are the same as in a circle of the same curvature.

PROPOSITION VIII.—PROBLEM III.

Let a body move in the semi-circumference $P Q A$; it is required to find the law of centripetal force, tending to a point S , so remote, that all lines $P S, R S$ drawn thereto, may be taken for parallel.—(Fig. 11.)

From C , the centre of the semi-circle, let the semi-diameter $C A$ be drawn, cutting those parallels per-

pendicularly in M and N, and let CP be joined. Because of the similar triangles CPM, PZT, and RZQ, CP² is to PM², as PR² to QT²; and, from the nature of the circle, PR² is equal to the rectangle QR × RN + QN; or, the points P and Q continually approaching, to the rectangle QR × 2PM. Therefore CP² is to PM², as QR × 2PM to QT²; therefore $\frac{QT^2}{QR} = \frac{2PM^3}{CP^2}$, and $\frac{QT^2 \times SP^2}{QR} = \frac{2PM^3 \times SP^2}{CP^2}$. And therefore (by Cor. 1 and 3, Prop. VI.) the centripetal force is reciprocally as $\frac{2PM^3 \times SP^2}{CP^2}$; that is, (neglecting the given ratio $\frac{2SP^2}{CP^2}$) reciprocally as PM³. Which was to be found.

The same thing is likewise easily collected from the preceding proposition.

SCHOLIUM.

And, by a like reasoning, a body will be found to move in an ellipse, or even in an hyperbola, or parabola, by a centripetal force, which is reciprocally as the cube of the ordinate, directed to a centre of force, at a very great distance.

PROPOSITION IX.—PROBLEM IV.

Let a body revolve in a spiral P Q S, cutting all the radii S P, S Q, &c. in a given angle; it is required to find the law of centripetal force, tending to the centre of that spiral. (Fig. 12.)

Let the indefinitely small angle P S Q be given; and because all the angles are given, the species of the figure S P R Q T will be given. Therefore the ratio $\frac{Q T}{Q R}$ is given; and $\frac{Q T^2}{Q R}$ is as Q T; that is,

(because the species of that figure is given,) as S P. But if the angle P S Q is any way changed, the right line Q R, subtending the angle of contact Q P R (Lem. XI.) will be changed in the duplicate ratio of

P R or Q T. Therefore the ratio $\frac{Q T^2}{Q R}$ remains the same as before; that is, as S P. Therefore $\frac{Q T^2 \times S P^2}{Q R}$ is as S P³, and (by Cor. 1. and 5,

Prop. VI.) the centripetal force is reciprocally as the cube of the distance S P. Which was to be found.

PROPOSITION X.—PROBLEM V.

Let a body revolve in an ellipse; it is required to find the law of centripetal force, tending to the centre of the ellipse. (Fig. 13.)

Let C A, C B be semi-axes of the ellipse, G F,

DK other conjugate diameters; PF, QT perpendiculars to those diameters; Qv an ordinate to the diameter GP; and if the parallelogram QvPR is completed, the rectangle PvG will be to Qv², as PC² to CD²; and (because of the similar triangles QvT, PCF) Qv² is to QT², as PC² to PF²; and by composition, the ratio of PvG to QT² is compounded of the ratio of PC² to CD², and of the ratio of PC² to PF²; that is, vG is to $\frac{QT^2}{Pv}$ as PC² to

$\frac{CD^2 \times PF^2}{PC^2}$. Substitute QR for Pv, and (by

Conics) BC × CA for CD × PF, also (the points P and Q, continually approaching) 2PC for vG; and multiplying the extremes and means together, we shall have $\frac{QT^2 \times PC^2}{QR}$ equal to

$\frac{2BC^2 \times CA^2}{PC}$. Therefore (by Cor. 5, Prop. VI.) the

centripetal force is reciprocally as $\frac{2BC^2 \times CA^2}{PC}$;

that is (because 2BC² × CA² is given) reciprocally as $\frac{1}{PC}$; that is, directly as the distance PC....

Which was to be found.

Cor. 1. And therefore, the force is as the distance of the body from the centre of the ellipse; and, on the contrary, if the force is as the distance, the body will move in an ellipse, whose centre coincides with

the centre of force ; or perhaps in a circle, into which the ellipse may be changed.

Cor. 2. And the periodical times of the revolutions made in all ellipses whatsoever about the same centre will be equal. For those times in similar ellipses are equal (by Cor. 3 and 8, Prop. IV.) but, in ellipses that have their greater axis common, they are to each other, as the whole areas of the ellipses directly, and the parts of the areas described in the same time inversely ; that is, as the less axes directly, and the velocities of the bodies in the principal vertices inversely ; that is, as those less axes directly, and the ordinates to the same point of the common axis inversely ; and therefore (because of the equality of the direct and inverse ratios) in the ratio of equality.

SECTION III.

OF THE MOTION OF BODIES IN ECCENTRIC CONIC SECTIONS.

PROPOSITION XI.—PROBLEM VI.

Let a body revolve in an ellipse ; it is required to find the law of centripetal force tending to the focus of the ellipse.
—(Fig. 14.)

Let S be the focus of the ellipse. Draw SP , cutting the diameter DK of the ellipse in E , and the ordinate Qv in x ; and let the parallelogram $QxPR$ be completed. It is evident that EP is equal to the greater semi-axis AC : for, drawing HI from the other focus H of the ellipse, parallel to EC , because CS, CH are equal, ES, EI will be also equal; so that EP is half the sum of PS, PI , that is, (because of the parallels HI, PR , and the equal angles IPR, HPZ ,) of PS, PH ; which taken together are equal to the whole axis $2AC$. Let QT be perpendicular to SP , and putting L for the principal *latus*

rectum of the ellipse (or for $\frac{2BC^2}{AC}$), $L \times QR$

will be to $L \times Pv$, as QR to Pv ; that is, as PE , or AC to PC ; and $L \times Pv$, to GvP , as L to Gv ; and GvP to Qv^2 as PC^2 to CD^2 ; and (by Cor 2, Lem. VII.) the points Q and P continually approaching without end, Qv^2 is to Qx^2 in the ratio of equality; and Qx^2 , or Qv^2 , is to QT^2 as EP^2 to PF^2 ; that is, as CA^2 to PF^2 ; or, (by Conics) as CD^2 to CB^2 . And compounding all these ratios together, $L \times QR$ is to QT^2 , as $AC \times L \times PC^2 \times CD^2$, or $2CB^2 \times PC^2 \times CD^2$, to $PC \times Gv \times CD^2 \times CB^2$, or as $2PC$ to Gv . But, the points Q and P continually approaching without end, $2PC$ and Gv are equal. Therefore the quantities $L \times QR$ and QT^2 proportional to these, are also equal. Let these equals be multiplied

into $\frac{SP^2}{QR}$, and $L \times SP^2$ will become equal to $\frac{SP^2 \times QT^2}{QR}$. Therefore (by Cor. 1. and 5. Prop.

VI.) the centripetal force is reciprocally as $L \times SP^2$; that is, reciprocally in the duplicate ratio of the distance SP . Which was to be found.

PROPOSITION XII.—PROBLEM VII.

Let a body move in an hyperbola: it is required to find the

law of centripetal force tending to the focus of that figure.
—(Fig. 15.)

Let CA, CB be the semi-axes of the hyperbola ; PG, KD other conjugate diameters ; PF a perpendicular to the diameter KD : and Qv an ordinate to the diameter GP . Let SP be drawn cutting the diameter DK in E , and the ordinate Qv in x , and let the parallelogram $QRPx$ be completed. It is evident, that EP is equal to the semi-transverse axis AC ; for, drawing HI from the other focus H of the hyperbola, parallel to EC , because CS, CH are equal, ES, EI will be also equal ; so that EP is half the difference of PS, PI ; that is (because of the parallels IH, PR , and the equal angles IPR, HPZ) of PS, PH ; the difference of which is equal to the whole axis $2AC$. Let QT be perpendicular to SP . And the principal *latus rectum* of the hyperbola (that is $\frac{2BC^2}{AC}$), being called L , we shall

have $L \times QR$ to $L \times Pv$, as QR to Pv , or Px to Pv ; that is (because of the similar triangles Pxv, PEC), as PE to PC , or AC to PC . Also $L \times Pv$ will be to $Gv \times Pv$, as L to Gv ; and (by the properties of the conic sections) the rectangle GvP is to Qv^2 , as PC^2 to CD^2 ; and (by Cor. 2, Lem. VII.) Qv^2 to Qx^2 , the points Q and P continually approaching without end, becomes a ratio of equality ; and Qx^2 or Qv^2 is to QT^2 , as EP^2 to PF^2 ; that is, as CA^2 to PF^2 , or (by Conics) as CD^2 to

CB^2 : and, compounding all these ratios together, $L \times QR$ is to QT^2 , as $AC \times L \times PC^2 \times CD^2$, or $2CB^2 \times PC^2 \times CD^2$ to $PC \times Gv \times CD^2 \times CB^2$; or as $2PC$ to Gv . But the points P and Q continually approaching without limit, $2PC$ and Gv are equal. Therefore the quantities $L \times QR$ and QT^2 , proportional to them, are also equal.

Let these equals be multiplied into $\frac{SP^2}{QR}$, and $L \times SP^2$ will be equal to $\frac{SP^2 \times QT^2}{QR}$. Therefore,

(by Cor. 1 and 5, Prop. VI.) the centripetal force is reciprocally as $L \times SP^2$; that is, reciprocally in the duplicate ratio of the distance SP . Which was to be found.

PROPOSITION XIII.—PROBLEM VIII.

Let a body move in the perimeter of a parabola: it is required to find the law of centripetal force, tending to the focus of that figure.—(Fig. 16.)

Let P be the body in the perimeter of the parabola, and from the place Q , into which the body is moving, draw QR parallel, and QT perpendicular to SP ; as also Qv parallel to the tangent, and meeting both the diameter PG in v , and the distance SP in x . Now, because of the similar triangles Pxv , SPM , and the equal sides SP , SM of the one, the sides

Px or QR and Pv of the other are also equal. But by the properties of the conic sections, the square of the ordinate Qv is equal to the rectangle under the *latus rectum*, and the segment Pv of the diameter; that is, (by Conics) to the rectangle $4PS \times Pv$, or $4PS \times QR$; and, the points P and Q approaching without limit, the ratio of Qv to Qx (by Cor. 2, Lem. VII.) becomes the ratio of equality. Therefore Qx^2 , in this case, becomes equal to the rectangle $4PS \times QR$. But (because of the similar triangles QxT , SPN) Qx^2 is to QT^2 , as PS^2 to SN^2 ; that is, (by Conics) as PS to SA ; that is, as $4PS \times QR$ to $4SA \times QR$, and therefore (by Prop. IX. Lib. V. Elem.) QT^2 , and $4SA \times QR$ are equal. Multiply these equals into $\frac{SP^2}{QR}$, and $\frac{SP^2 \times QT^2}{QR}$ will become equal to $SP^2 \times 4SA$;

and therefore (by Cor 1 and 5, Prop. VI.) the centripetal force is reciprocally as $SP^2 \times 4SA$; that is, because $4SA$ is given, reciprocally in the duplicate ratio of the distance SP . Which was to be found.

Cor. 1. From the three last propositions it follows, that if any body P goes from a place P , with any velocity, in the direction of any right line PR , and at the same time is urged by the action of a centripetal force, which is reciprocally proportional to the square of the distance of the places from the centre; this body will move in one of the conic sections, hav-

ing its focus in the centre of force ; and the contrary. For, the focus, the point of contact, and the position of the tangent being given, a conic section may be described, which at that point shall have a given curvature. But the curvature is given from the centripetal force and the velocity of the body being given, and two orbits, mutually touching each other, cannot be described by the same centripetal force, and the same velocity.

Cor. 2. If the velocity, with which the body goes from its place P, is such, that in any indefinitely small moment of time the line P R may be thereby described ; and the centripetal force is such, as in the same time to move that body through the space Q R ; the body will move in one of the conic sections ; whose principal *latus rectum* is the limit, to which the quantity $\frac{Q T^2}{Q R}$ approaches, while the lines P R, Q R are continually diminished.

In these corollaries I consider the circle as an ellipse ; and I except the case, where the body descends to the centre in a right line.

PROPOSITION XIV.—THEOREM VI.

If several bodies revolve about one common centre, and the centripetal force is reciprocally in the duplicate ratio of the distance of places from the centre ; I say, that the principal latera recta of their orbits are in the duplicate ratio

of the areas, which the bodies, by radii drawn to the centre, describe in the same time.—(Fig. 8.)

For (by Cor. 2, Prop. XIII.) the *latus rectum* L is equal to the limit, to which the quantity $\frac{Q T^2}{Q R}$ approaches, while the distance of P and Q is continually diminished. But the small line Q R, in a given time, is as the generating centripetal force; that is, (by supposition) reciprocally as $S P^2$. Therefore $\frac{Q T^2}{Q R}$ is as $Q T^2 \times S P^2$; that is, the *latus rectum* L is in the duplicate ratio of the area Q T \times S P. Which was to be demonstrated.

Cor. Hence the whole area of the ellipse, and the rectangle under the axes, proportional to it, is in the ratio compounded of the subduplicate ratio of the *latus rectum*, and the ratio of the periodical time. For, the whole area is as the area Q T \times S P, which is described in a given time, multiplied into the periodical time.

PROPOSITION XV.—THEOREM VII.

The same things being supposed, I say, that the periodical times in ellipses are in the sesquuplicate ratio of their greater axes.

For the less axis is a mean proportional between the greater axis and the *latus rectum*; and, therefore, the rectangle under the axes is in the ratio com-

pounded of the subduplicate ratio of the *latus rectum*, and the sesquiplicate ratio of the greater axis. But this rectangle (by Cor. Prop. XIV.) is in a ratio, compounded of the subduplicate ratio of the *latus rectum*, and the ratio of the periodical time. Subtract from both sides the subduplicate ratio of the *latus rectum*, and there will remain the sesquiplicate ratio of the greater axis equal to the ratio of the periodical time. Which was to be demonstrated.

Cor. Therefore, the periodical times in ellipses are the same as in circles, whose diameters are equal to the greater axes of the ellipses.

PROPOSITION XVI.—THEOREM VIII.

The same things being supposed, and right lines being drawn to the bodies, which touch the orbits; and perpendiculars being let fall on these tangents from the common focus: I say, that the velocities of the bodies are in a ratio compounded of the ratio of the perpendiculars inversely, and the subduplicate ratio of the principal latera recta directly.—(Fig. 8.)

From the focus *S* draw *SY* perpendicular to the tangent *PR*, and the velocity of the body *P* will be reciprocally in the subduplicate ratio of the quantity $\frac{SY^2}{L}$. For that velocity is as the indefinitely small arc *PQ* described in a given moment of time; that is, (by Lem. VII.) as the tangent *PR*; that is, be-

cause of the proportionals PR to QT and SP to SY , as $\frac{SP \times QT}{SY}$, or as SY reciprocally and $SP \times QT$ directly; but $SP \times QT$ is as the area described in a given time; that is, (by Prop. XIV.) in the subduplicate ratio of the *latus rectum*. Which was to be demonstrated.

Cor. 1. The principal *latera recta* are in a ratio compounded of the duplicate ratio of the perpendiculars, and the duplicate ratio of the velocities.

Cor. 2. The velocities of the bodies, in their greatest and least distances from the common focus, are in the ratio compounded of the ratio of the distances inversely, and the subduplicate ratio of the principal *latera recta* directly. For the perpendiculars are now the distances.

Cor. 3. And therefore the velocity in a conic section, at its greatest or least distance from the focus, is to the velocity in a circle at the same distance from the centre, in the subduplicate ratio of the principal *latus rectum* to double that distance.

Cor. 4. The velocities of bodies revolving in ellipses, at their mean distances from the common focus, are the same as those of bodies revolving in circles, at the same distances: that is, (by Cor. 6, Prop. IV.) reciprocally in the subduplicate ratio of the distances. For the perpendiculars are now the less semi-axes, and these are as mean proportionals between the distances and the *latera recta*. Let this ratio inversely be compounded with the subduplicate ratio of the

latera recta directly, and we shall have the subduplicate ratio of the distances inversely.

Cor. 5. In the same figure, or even in different figures, whose principal *latera recta* are equal, the velocity of a body is reciprocally as the perpendicular let fall from the focus on the tangent.

Cor. 6. In a parabola, the velocity is reciprocally in the subduplicate ratio of the distance of the body from the focus of the figure: in the ellipse it is more varied, and in the hyperbola less than according to this ratio. For (by Conics) the perpendicular let fall from the focus on the tangent of a parabola is in the subduplicate ratio of the distance. In the hyperbola the perpendicular is less varied; in the ellipse more.

Cor. 7. In a parabola, the velocity of a body, at any distance from the focus, is to the velocity of a body revolving in a circle at the same distance from the centre, in the subduplicate ratio of the number 2 to 1; in the ellipse it is less, and in the hyperbola greater, than according to this ratio. For (by *Cor. 2* of this *Prop.*) the velocity at the vertex of a parabola is in this ratio, and (by *Cor. 6* of this *Prop.* and *Prop. IV.*) the same proportion is preserved in all distances. And hence also in a parabola the velocity is every where equal to the velocity of a body revolving in a circle at half the distance; in an ellipse it is less; in an hyperbola greater.

Cor. 8. The velocity of a body, revolving in any conic section,* is to the velocity of a body revolving in a circle, at the distance of half the principal *latus*

rectum of the section, as that distance, to the perpendicular let fall from the focus on the tangent of the section. This appears by Cor. 5.

Cor. 9. Since (by Cor. 6, Prop. IV.) the velocity of a body, revolving in this circle, is to the velocity of a body, revolving in any other circle, reciprocally in the subduplicate ratio of the distances; therefore *ex æquo* the velocity of a body, revolving in a conic section, will be to the velocity of a body revolving in a circle at the same distance, as a mean proportional between that common distance, and half the principal *latus rectum* of the section, to the perpendicular let fall from the common focus upon the tangent of the section.

FINIS.

NOTES,

&c.

TO THE

THREE PRECEDING SECTIONS.

GENERAL INTRODUCTION

TO THE

THREE SECTIONS.



Of the Method of Exhaustions.

Art. 1. BEFORE we enter upon the consideration of the doctrine of Prime and Ultimate Ratios, it may be of use to observe the steps by which the ancients were able, in several instances, from the mensuration of right-lined figures, to judge of such as are bounded by curve lines: *for as they did not allow themselves to resolve curvilinear figures into rectilinear elements,* it is worth while to examine by what art they could make a transition from the one to the other.

2. They found that similar triangles are to each other in the duplicate ratio of their homologous sides; and by resolving similar polygons into similar triangles, the same proportion was extended to these polygons also. But when they came to compare curvilinear figures, which cannot be resolved into rectilinear parts, this method failed. In these instances, they had recourse to what is called the Method of Exhaustions; the principle of which consisted, first, in describing upon the curvilinear space a rectilinear

one, which, though not equal to the other, yet might differ less from it than by any assignable quantity; and secondly, in investigating the truth or falsehood of every supposition that could possibly be made contrary to the proposition to be proved; and by reducing every such supposition to an absurdity, thence indirectly inferring the truth of the proposition itself. For instance, in comparing the areas of two circles, they inscribed in each similar polygons, which, by increasing the number of their sides, continually approached to the areas of the circles, so that the decreasing differences betwixt each circle and its inscribed polygon, by still further and further divisions of the circular arcs, could become less than any quantity that can be assigned: they found that all this while the similar polygons observed the same invariable ratio to each other, viz. that of the squares of the diameters of the circles. Upon this they founded their demonstration; and by shewing that some absurdity must follow if we suppose the circles to be to each other in a greater or in a less ratio than the squares of the diameters, they concluded that they must be in that very ratio. But as one complete instance may serve better than any general description, to exemplify their reasoning, let the following Theorem be proposed to be demonstrated by the Method of Exhaustions.

3. *The area of a circle is equal to half the product of its radius and circumference.*—(Fig. 17.)

Let bd , the base of the right $\triangle abd$, be supposed equal to the circumference of the circle ABD , $ab =$ radius CA , $EFGH$ any equilateral polygon described about the circle, $ABDK$ a similar polygon inscribed in it. As the circumscribed polygon $EFGH$ is greater than the circle, so it is greater than the triangle abd (being $=$ to a \triangle whose altitude is CA or ab , and base $=$ perimeter $EFGH$,

which is always greater than bd , the circumference of the \odot). The inscribed polygon is less than the \odot , and it is also less than the $\triangle abd$, (being = to a \triangle whose altitude = CQ , which is less than CA or ab , and base = to its perimeter $ABDK$, which is less than the circumference bd); \therefore the \odot and the $\triangle abd$ are both constantly limits betwixt the external and internal polygons $EFGH$, $ABDK$. Let the arc AB be bisected in L , and the tangent at L meet AE , BE in M and N , and the $\angle ELM$ being a right \angle , EM must be greater than LM or MA , the $\triangle ELM$ greater than ALM , and EMN greater than the sum of the $\triangle ALM$, BLN , and consequently greater than half the space $EALB$, bounded by the tangents EA , EB , and the arc ALB ; \therefore (by Euclid 1. 10 B, the foundation of this method) the circumscribed polygon may approach to the \odot nearer than by any assignable quantity. The inscribed polygon may also approach to the \odot nearer than by any assignable quantity, as is shewn in the Elements of Euclid, \therefore the \odot and the $\triangle abd$, which are both limits betwixt these polygons, must be equal to each other. For if the $\triangle abd$ be not = to the circle, it must either be greater or less than it. If the $\triangle abd$ be greater than the \odot , then since the external polygon, by encreasing the number of its sides, may be made to approach the \odot so as to exceed it by a quantity less than any difference that can be supposed to exist between it and the $\triangle abd$, it follows that the external polygon may become less than that \triangle , which is absurd. If the $\triangle abd$ be less than the \odot , then the inscribed polygon, by being made to approach the \odot , may exceed that \triangle , which is also absurd: Hence the circle and \triangle are equal to each other.

4. Archimedes in this demonstration does not suppose the circle to coincide with a circumscribed equilateral polygon of an infinite number of sides, but proceeds in a more accurate and unexceptionable manner.

And in this consists the error of many writers, who have asserted that curve lines were considered by the ancient geometers as polygons of an infinite number of sides. But this principle no where appears in their writings; we never find them resolving any figure or solid into infinitely small elements: on the contrary, they seem to avoid such suppositions, even when their demonstrations might have been sometimes abridged by admitting them. For instance, if they could have allowed themselves to have considered circles as similar polygons of an infinite number of sides; after proving that any similar polygons inscribed in circles are in the duplicate ratio of their diameters, they would have immediately extended this to the circles themselves. But there is ground to think, that they would not have admitted a demonstration of this kind. It was a fundamental principle with them, on which, as Archimedes expressly asserts, they founded their propositions on curvilinear figures, that the difference of any two unequal quantities may be added to itself until it exceed any proposed finite quantity of the same kind. But this principle seems to be inconsistent with the admitting of an infinitely small quantity or difference, which added to itself any number of times, is never supposed to become equal to any finite quantity whatsoever. The ancients, therefore, considered curvilinear areas as the limits of circumscribed or inscribed figures of a more simple kind, which approach to these limits, (by a bisection of lines or angles, that is continued at pleasure) so that the difference betwixt them may become less than any given quantity. The inscribed or circumscribed figures were always conceived to be of a magnitude and number that is assignable; and from what had been shewn of these figures, they demonstrated the mensuration or the proportions of the curvilinear limits themselves, by arguments *ab absurdo*.

Of the Method of Indivisibles.

5. The doctrine of Exhaustions, as delivered by Archimedes, being considered tedious and prolix by the modern geometers, various methods were proposed for the purpose of simplifying and abridging his demonstrations. It was thought unnecessary to conceive the figures circumscribed about, or inscribed in, the curvilinear area or solid, as being always assignable and finite; and, therefore, instead of the assignable finite figures of Archimedes, indivisible or infinitely small elements were substituted, and these being imagined indefinite or infinite in number, their sum was supposed to coincide with the curvilinear area or solid.

6. It was upon these principles that Cavalerius, in the 17th century, founded what is called the Method of Indivisibles. In this doctrine, lines were conceived to be made up of an indefinite number of points, superficies of lines, and solids of superficies; and in computing the magnitudes or proportions of areas or solids, they computed the sum of all the indivisible elements of which the area or solid is composed. Thus for example, a Δ was conceived to be made up of an indefinite number of lines parallel to the base, and consequently the area of the Δ was equal to the sum of all these parallel lines. Now to find the sum of these parallel lines, we have only to conceive them as a set of quantities in arithmetical progression—the 1st term being 0, and the last term the base of the Δ , and the number of terms the perpendicular; \therefore the sum of the series, or the area of the Δ , will = base $\times \frac{1}{2}$ the perpendicular.

7. Ex. 2.—*To find the ratio betwixt the sphere and its circumscribing cylinder by the method of indivisibles.—*
(Fig. 18.)

Let the cylinder N M, the cone N O R, and the

hemisphere $M T S$ be cut by planes parallel to the base, one of which is $C S K D C$; then $S O^2 = C D^2 = S D^2 + D O^2 = S D^2 + D K^2$, $\therefore C D^2 = S D^2 + D K^2$; and this is true for every section parallel to the base; \therefore since the circles of which these lines are the $\frac{1}{2}$ diameters are as the squares of the said $\frac{1}{2}$ diameters, it follows that the sum of all the circles in the $\frac{1}{2}$ sphere, together with the sum of all the circles in the cone = the sum of all the circles in the cylinder; the cylinder itself \therefore , which is composed of these circles, is = to the $\frac{1}{2}$ sphere and cone together; but the cone is a third part of the cylinder; this therefore being deducted, there remains $\frac{1}{2}$ sphere : cylinder $\therefore 2 : 3$.

8. In this doctrine then we see, that by the admission of infinitely small quantities, the old foundation of geometry was abandoned, and suppositions resorted to which had been avoided by Archimedes. And though the new geometry had much the advantage over the ancient in point of conciseness; yet the former was much inferior to the other in the certainty of its deductions. For as this doctrine was inconsistent with the strict principles of geometry, so it soon appeared that there was some danger of its leading to false conclusions. And after men had indulged themselves in admitting quantities that were not assignable, and in supposing such things to be done as could not possibly be effected (against the constant practice of the ancients), and had involved themselves in the mazes of infinity, it was not easy for them to avoid perplexity, and sometimes error.

9. To shew the caution which should be used in the application of this doctrine, the following example may be sufficient. If a \odot be considered as a polygon of an infinite number of sides, and \therefore an infinitely small arc be supposed perfectly to coincide with its chord, it follows that the time of the vibration of a pendulum in this arc = the time of descent down its chord;—but, by mechanics, the ratio of the

times is that of the quadrant of a \odot to its diameter. Nor can this difficulty be removed except the arc be again divided into an infinite number of indivisible elements, infinitely less than the former ; *i. e.* we must have recourse to infinitesimals of the 2d order.*

Of the Doctrine of Prime and Ultimate Ratios.

Art. 10. Having taken a general view of the ancient geometry, as it existed in the time of Archimedes, and the changes effected in it by the modern mathematicians, previous to Newton's time ; we may now proceed to the consideration of the doctrine of Prime and Ultimate Ratios, which was invented by Sir I. Newton, for the purpose, as he himself says, of avoiding, on the one hand, the tedious demonstrations of the ancient, and on the other, the inaccurate and objectionable positions of the modern geometers. In this doctrine, magnitudes are not supposed to consist of indivisible parts, but to be generated by continued motion. *Lineæ nempe (as Newton says) describuntur, ac describendo generantur, non per appositionem partium, sed per motum continuum punc-*

* There is no such difficulty when the method of prime and ultimate ratios is applied to this case ; for, though the arc and chord approximate to equality, the times of descending along them do not approximate ; for, by the doctrine of limits, no part of a curve, how small soever, can ever be taken for a right line : but even when they so far approach to each other, that their lengths may be taken as equal, the curve still remains a curve ; its inclination is different from that of the chord ; the accelerating force along the curve perpetually varies, while the accelerating force along the chord remains constant, and consequently the times of describing these spaces are unequal, even supposing their lengths the same.

torum; superficies per motum linearum, solida per motum superficierum, anguli per rotationem laterum, tempora per fluxum continuum, & sic in cæteris. Hæ geneses in rerum naturâ locum verè habent, & in motu corporum quotidie cernuntur. This method of conceiving all variable quantities to be generated by motion is the characteristic feature, which distinguishes both this doctrine, and also that of fluxions.

11. This being premised, we now go on to the doctrine itself, the principle of which is contained in the following definition :—Let there be two quantities, one fixed, and the other varying, so related to each other that (1) The varying quantity, by a perpetual augmentation or diminution, continually approaches to the fixed quantity. (2) That the varying quantity does never pass beyond or even actually reach that which is fixed. (3) That the varying quantity approaches nearer to the fixed quantity than by any assignable difference; then, upon the fulfilment of these three conditions, the fixed quantity is called the *Limit* or *Ultimate Magnitude* of the varying quantity.

12. *Ex.*—According to this definition the \odot described Art. 3, is the *limit* of the polygon circumscribing it. For, as was shewn in that Art., (1) this polygon, by encreasing the number of its sides, continually approaches to the area of the \odot . (2) It can never become less than the \odot , or even equal to it. (3) By continually encreasing the number of its sides, it may at length approach nearer to the \odot than by any assignable quantity. The \odot \therefore having the conditions laid down in the last Art. is the *limit* of the polygon.

13. The explanation given in Art. 11, of quantities which have limits, is also to be extended to the limits of ratios. The definition may be thus stated. If there be two quantities that are (one or both) continually varying, either by being continually aug-

mented, or continually diminished; and if the ratio they bear to each other does, by this means, perpetually vary, but in such a manner, that (1) this varying ratio continually approaches to some determined ratio; (2) that the varying ratio does never pass beyond, or even actually reach, the fixed ratio; (3) that the varying ratio approaches nearer to the fixed ratio than to any other that can be assigned: then, upon the fulfilment of these three conditions, the determined ratio is called the *limiting* or *ultimate* ratio of the varying one.

14. *Ex. 1.*—Let x be any varying quantity; make $4x^2 + 3x = A$, and $2x^2 + x = B$, then will A and B also be varying quantities, as depending upon x ; when x vanishes, A and B will both vanish; and when x is infinite, they will both be infinite: I say, that the determined $R^\circ. 3 : 1$ is the limiting $R^\circ.$ of $A : B$, while x decreases in infinitum. For the $R^\circ. A : B =$ the $R^\circ. 4x^2 + 3x : 2x^2 + x$; \therefore (1) as x decreases, $A : B$ approaches to the $R^\circ. 3 : 1$; (2) the $R^\circ. A : B$ can never exceed, or even reach, that of $3 : 1$; for $6x^2 + 3x : 2x^2 + x :: 3 : 1$, but $6x^2 + 3x$ is greater than $4x^2 + 3x$; $\therefore 4x^2 + 3x$ is always in a less $R^\circ.$ to $2x^2 + x$ than the $R^\circ. 3 : 1$; (3) the Ratio $A : B$ will approach nearer to that of $3 : 1$, than to any other that can be proposed; for $4x$ and $2x$ may become less than any assignable quantity, by the diminution of x ; consequently the $R^\circ. 3 : 1$ is the limiting $R^\circ.$ of $4x^2 + 3x : 2x^2 + x$.

Ex. 2.—Taking the same $R^\circ.$ as before; I say, that while x increases in infinitum, the determined $R^\circ. 2 : 1$ is the limiting $R^\circ.$ of $A : B$; for the given $R^\circ. =$ that of $4 + \frac{3}{x} : 2 + \frac{1}{x}$; \therefore (1) the Ratio $A : B$ approaches that of $2 : 1$; for as x increases $\frac{3}{x}$ and $\frac{1}{x}$ decrease; (2) the $R^\circ. A : B$ can never be

less than, or even equal to, the R°. $2 : 1$; for $4x^2 + 2x : 2x^2 + x :: 2 : 1$; $\therefore 4x^2 + 3x$ is always to $2x^2 + x$ in a greater R°. than that of $2 : 1$; (3) the R°. $A : B$ will approach nearer to that of $2 : 1$ than to any other that can be proposed; for $\frac{3}{x}$ and $\frac{1}{x}$, by increasing x , may become less than any assignable quantity; consequently the R°. $2 : 1$ is the limiting R°. of $4x^2 + 3x : 2x^2 + x$.

15. We see then in the two last Examples, that though diminishing x , and consequently diminishing the terms A and B , increases their R°.; and contrariwise increasing these terms, by increasing x , decreases their R°.; yet there is a limit both to the increase and decrease of this R°. , though there is none to the terms themselves that compose it, which, as we have seen, in the first case decrease, and in the other increase, in infinitum.

16. We will close these Examples, by proposing a geometrical one, for the purpose of more clearly explaining Newton's phrases of "Ratio ultima quantitatum evanescentium," and "Ratio prima quantitatum nascentium." Let (*Fig. 19*) $ABCD$, $EBCF$ be two quadrilateral figures, and let DF be parallel to AE ; then the quadrilateral $ABCD$ bears to the quadrilateral $EBCF$ the proportion of $AB + DC$ to $EB + CF$. Now if the line DF be supposed to advance towards AE , with an uninterrupted motion, till the quadrilaterals quite disappear or vanish, this proportion of $AB + DC : EB + CF$ will, during this motion, continually vary, (unless the lines DA , CB , FE produced meet in the same point; which they are not here supposed to do) and this proportion, by diminishing the distance between DF and AE , may at last be brought nearer to the proportion of $AB : BE$ than to any other whatever; though it can never exceed, or even actually reach, this proportion; \therefore the proportion of $AB : BE$ is

the limiting or ultimate proportion of the quadrilateral $A B C D$: the quadrilateral $E B C F$, because it is the proportion which these quadrilaterals can never actually have to each other, but the limit of that proportion.

In this Ex. then, as in the other above given, the quantities themselves, *i. e.* the quadrilaterals, have neither of them any final magnitude, or even so much as a limit; but, by the diminution of the distance between $D F$ and $A E$, diminish continually without end; yet there is a limit to the varying proportion existing between them, viz. that of $A B : B E$; and hence this limit is to be called the *ultimate* R^o . of the *vanishing* quadrilaterals.

17. But that the meaning of the expression “Ratio ultima quantitatum evanescentium” may be still more clearly understood, we may further observe, (1) That since the quadrilaterals diminish by a continual motion till they actually vanish, they may properly be called *vanishing* quantities; since under this view they have never any stable magnitude, but decrease by a continued motion till they become nothing. (2) That the quadrilaterals $A B C D$, $B E F C$, become vanishing quantities, from the time we first ascribe to them this perpetual diminution, *i. e.* from that time they are quantities going to vanish. And as during their diminution they have continually different proportions to each other; so the R^o . between $A B$ and $B E$ is not to be called merely Ratio harum quantitatum evanescentium; but *ultima* Ratio, &c. and the same observations are applicable to the Example given in Art. 14.

18. Should we suppose the line $D F$ first to coincide with the line $A E$, and then to recede from it, thus giving birth to the quadrilaterals; then under this conception, the R^o . $A B : B E$, as it was before called the R^o . wherewith the quadrilaterals *vanish*, is now to be considered as the R^o . wherewith the quadrilaterals by this motion *commence*; and the R^o . may

also properly be called the *first* or *prime* R^o . of these quadrilaterals *at their origin*.

19. As in Art. 17, the phrase *vanishing* quantities was applied to the quadrilaterals, from the time that they are quantities going to vanish ; so, under the present conception, they are to be called *nascentes*, not only at the very instant of their first production, but according to the sense in which such participles are used in common speech ; just as when we say of a body, which has lain at rest, that it is beginning to move, though it may have been some little time in motion. On this account we must not use the simple expression, Ratio quantitatum nascentium, but Ratio *prima* quantitatum nascentium.

20. We see here the same R^o . may be called sometimes the *Prime*, at other times the *Ultimate*, R^o . of the same varying quantities, according as these quantities are considered under the notion of vanishing, or of being produced, before the imagination, by an uninterrupted motion. The doctrine under examination receives its name from both these ways of expression.

The reader having now, it is hoped, gained a correct idea of the limit or ultimate magnitude of a variable quantity and ratio, may proceed with advantage to the first Lemma, wherein it is demonstrated that the limits or ultimate magnitudes of two variable quantities, or two variable ratios, approaching to each other as there described, are accurately equal.

NOTES TO SECTION I.

LEMMA I.

21. *Case 1.*—Let there be two variable quantities x and y , which continually approach to equality, so that their difference, when compared with either of them, becomes at length less than any assignable quantity; then will x and y be ultimately equal: in other words, if a be the ultimate magnitude of x , and b the ultimate magnitude of y , these limits a and b will be accurately equal. For if not, let these limits have a difference, d , *i. e.* let $b = a + d$; then since a is the limit of x , x can never exceed a , and \therefore can never come nearer to $a + d$, the limit of y , than by the given difference d ; *i. e.* x and y , even in their ultimate state, can never approach nearer to each other than by the given difference d ; which is contrary to the hypothesis: $\therefore a$ does accurately $= b$, *i. e.* x and y are ultimately equal. Here x has been supposed to be less than its limit a ; but the Prop. may be proved after the same manner, if x be supposed to be greater than a .

Case 2. Let there be two variable Ratios $x : y$ and $v : z$, which continually approach to equality; so that at length the R^o. $x : y$ approaches nearer to that of $v : z$ than to any other that can be assigned; then

will the $R^\circ. x : y$ be ultimately $=$ the $R^\circ. v : z$; in other words, if $m : n$ be the limiting $R^\circ.$ of $x : y$, and $p : q$ the limiting $R^\circ.$ of $v : z$, the $R^\circ. m : n$ shall accurately $=$ that $p : q$. For if not, let there be any given difference between them; then, since the Ratios $x : y$ and $v : z$ can never actually reach their limits $m : n$ and $p : q$; it follows, that $x : y$ and $v : z$ can never approach nearer to equality than by this given difference, which is contrary to the hypothesis; \therefore the $R^\circ. m : n$ does accurately $=$ that of $p : q$; *i. e.* the Ratios $x : y$ and $v : z$ are ultimately equal.

Or both cases may be concisely proved, by observing, that both quantities, and the Ratios of quantities, such as are understood in the Lemma, cannot approach nearer to each other than their limits do; and hence the absurdity of supposing these limits unequal is immediately apparent.

LEMMA III.

Note to Lemma 3.

22. What is here proved of the *areas* of the inscribed and circumscribed figures is not true of the *perimeters*; for the \angle^r boundary of the circumscribed always remains the same, being $= Aa + AE$, whatever be the number of divisions; and \therefore never approaches the curvilinear boundary as a limit; and the \angle^r boundary of the inscribed approaches that of the circumscribed as a limit, and is always greater than the curvilinear boundary. Hence Newton's *ultimate sum* in Cor. 1 must be strictly confined to area.

Lem. 3.—Cor. 3.

23. For (*Fig. 20*) one of the lines at least in each pair al , lb , bm , mc , cn , nd , must cut the curve, consequently one of the lines at least in each pair must make a greater \angle with the curve than the tangents do; hence the Δ^s apb , boc , crd , formed by the tangents, will fall within the mixtilinear spaces alb , bmc , cnd , and \therefore be less than them; consequently since $Aalbmcnd$ is ultimately = the curvilinear area, much more will the area $Aapbocrd$ be ultimately = the same curvilinear area.

Notes to Lem. 3.—Cor. 4.

24. The *ultimate figures* here spoken of must be applied only to the figures of the chords and tangents, since the \angle^r perimeters above mentioned, have not the curve line for their limit. The Cor. so far as relates to the chords, is perfectly evident; if the reader should not think it equally so for the figure formed by the tangents, he may see a proof of it in Art. 34.

25. *Curvilinear limits of rectilinear figures.* See Scholium to Lemma XI., where Newton again cautions his readers,* that if at any time he should, for right lines, substitute curve lineolæ, they are not to understand that these lineolæ are made up of right lines, however small, (agreeably to the doctrine of Indivisibles) but that the curves are the limits, to which the vanishing right lines continually approach, and ultimately equal.

* "Si pro rectis usurpavero lineolas curvas, nolim indivisibilia, sed evanescentia divisibilia."

LEMMA IV.

26. For, by hypothesis, $A' : a' :: B' : b' :: C' : c'$ ultimately; $\therefore A' : a' :: A' + B' + C' : a' + b' + c'$ ultimately; but ultimately $A' + B' + C' =$ whole figure $A a E$, and $a' + b' + c' =$ whole figure $P p T$; \therefore under the conditions mentioned in the Lemma, $A a E : P p T$ in the given R° . of $A' : a'$.

LEMMA V.

Introductory Article to Lemma 5.

27. *Definition.*—Curvilinear figures, when referred to a centre, are said to be similar, when they may be supposed to be placed in such a manner, that any right line being drawn from a determined point to the terms that bound them, the parts of the right line, intercepted betwixt that point and those terms, are always in one constant R° . to each other: or, in other words, they are similar, when the rad. vect^s. containing equal \angle^s are always proportional. Thus the curvilinear figures $A S D$, $a S d$, (*Fig. 21*) or the figures $S P D$, $S p d$ are similar, when any line $S P$ being drawn always from the same point S , meeting the two curves in P, p , the R° . of $S P : S p$ is invariable.

Lemma 5.

28. (1) Let $S A D$, $s a d$ (*Fig. 22*) be two similar curvilinear figures, and let $S A P Q D$ be any polygon inscribed in the former; draw $s p, s q$, &c., making the \angle^s at s respectively = the \angle^s at S ; then since by definition $S A : S P :: s a : s p$, and $\angle A S P = \angle a s p$, the $\triangle^s A S P$, $a s p$ are similar; and the same may be shewn of all the remaining \triangle^s , \therefore poly-

gon $sapqd$ is similar to the polygon $SAPQD$; and hence $AP : PQ :: ap : pq$; and $PQ : QD :: pq : qd$; $\therefore AP : ap :: PQ : pq :: QD : qd$, &c., and this is true when the number of the sides AP , ap , PQ , pq , &c. is increased, and their magnitude diminished without limit; \therefore (by Cor. Lem. IV.) curve $APD : \text{curve } apd :: AP : ap :: SA : sa$.

29. (2) Taking the same construction as before, since the polygons $SAPQD$, $sapqd$ are similar, the Δ ' into which they are divided will be similar; $\therefore \Delta SAP : \Delta sap :: \Delta SPQ : \Delta spq :: \Delta SQD : \Delta sqd$, &c.; \therefore as before, curvilinear area $SAD : \text{curvilinear area } sad :: \Delta SAP : \Delta sap :: SA^2 : sa^2$.

LEMMA VI.

Introductory Articles to Lemma 6.

30. A curve of *continued* curvature may be defined to be a line traced out by a point, *continually* changing its direction; where we may observe that the word *continually* implies that the change of direction of the generating point must not be effected by starts or impulses (*per saltum*), but by an uninterrupted and equable motion. Thus the $\angle BCD$ (*Fig. 23*), which measures the variation of direction of the generating point at A and B, (while the point moves from B to A) must, before it become nothing, pass through all the intermediate degrees of magnitude, from $\angle BCD$ to nothing.

31. From this definition, it will appear that two curves which cut one another, as Ed , dF , (*Fig. 24*) cannot be called a curve of continued curvature at the point d ; for if a and c be taken on opposite sides of d , the variation of direction from a to c , viz. the \angle

$c b g$ has been effected *per saltum*; *i. e.* in passing from nothing to $c b g$, the \angle has not passed through all the intermediate degrees of magnitude.

32. From hence also it follows, (1) That if the distance betwixt two positions of the generating point continually decrease, and at length ultimately vanish, the change of direction of this point will also continually decrease, and at length ultimately vanish; *i. e.* while B moves up to A (*Fig. 23*) the $\angle B C D$ is decreasing continually without limit, till at last, when A B ultimately vanishes, the $\angle B C D$ also ultimately vanishes. (2) That the direction of the generating point is a tangent to the curve; for, suppose A D to be the direction of the generating point at A, then, if it did not change its direction, it would move along the line A D; but, by the definition, it is continually changing its direction; \therefore if it be in the line A D at A, it will not continue in it, but will, in the next moment of time, go either above or below it; \therefore A D is a tangent to the curve at A. (3) That A D is the only tangent; for, if possible, let A V (*Fig. 25*) making a finite \angle with A D, be a tangent, let the point B move up to A, so that the change of direction B C D may be indefinitely small, then will B C D be indefinitely less than D A V; \therefore a fortiori will the interior \angle , formed by the curve and tangent D A, be indefinitely less than D A V; *i. e.* D A passes indefinitely nearer the curve than any other line A V that can be drawn.

Lemma 6.

33. After what has been premised, the Lemma may be easily proved thus. Let A, B (*Fig. 25*) be two positions of the generating point, draw the chord A B, and at the points A, B, draw A C, B C in the direction of the generating points at A and B respectively; then A C, B C are tangents to the curve, (Art. 32.) Now, by the continual approach of B to A, the change of direction of the generating point

will continually decrease, and at length ultimately vanish, (Art. 32) *i. e.* the $\angle BCD$ will ultimately vanish; a fortiori \therefore will the interior $\angle BAD$, contained by the chord and tangent, ultimately vanish.

Note to Lemma 6.

§4. By the help of this Proposition, Cor. 4. Lem. III. may be easily proved. Let the two lines AD , DB (*Fig. 26*), which touch the curve ACB of continued curvature in the points A , B meet each other in D , and the chord AB be drawn; the sum of the tangents will be greater than the chord; and if the curve be divided into any two parts in the point C , and the chords AC , CB be drawn, and also EF a tangent to the curve in the point C , meeting the tangents AD , BD in E and F , the sum of the chords AC , CB will be greater than the first chord AB ; and the sum of the tangents AE , EC , CF , FB , greater than the sum of the chords: but AE , EF being less than AD , DF ; AE , EF , FB will be less than AD , DB . Hence, if the number of parts, into which the curve ACB is divided, be continually increased, the sum of the chords will be continually increased, and the sum of the tangents continually diminished; and the latter sum being always greater than the former, the difference between them will continually decrease; and as the \angle between the chords and tangents may be diminished without limit, (Art. 33) this difference may be also diminished without limit. Hence the difference between the perimeters of the figures, contained by the two lines AD , AE , (*Fig. 1*) and the chords, and by the same two lines and the tangents, will be continually diminished, as the bases AB , BC , CD , &c. are diminished; and the perimeter of the curvilinear figure will be a limit to them both.

LEMMA VII.

Introductory Article to Lemma 7.

35. It follows from the definition of similar curvilinear figures given in Art. 27, (1) that to draw a curve Acb similar to another ACB (*Fig. 27*), we must produce AB to any point b , and, while Ab revolves round A as a centre, let the point b move in the line Ab , so that Ab may be to AB in a given R° ; then will Acb be similar to ACB ; (2) that if AD be a tangent to ACB at A , it will also be a tangent to the similar curve Acb at A ; for draw bd parallel to BD , then by similar \triangle^s , $bd : BD :: Ab : AB$, in a given R° ; $\therefore bd$ will not vanish till BD vanishes, *i. e.* at the point A .

Lemma 7.

36. Produce AD (*Fig. 27*) to any distant point d , and let db be drawn parallel to DB , meeting the chord AB produced in b ; and through the point b describe, as has been above shewn, the curve Acb continually similar to ACB , to which Ad will be a tangent; then, by similar \triangle^s , $AB : AD :: Ab : Ad$; and by similar figures (*Lem. 5.*) $ACB : Acb :: AB : Ab$, or as $AD : Ad$; \therefore the chord, arc, and tangent AB , ACB , and AD are always proportional to the chord, arc, and tangent Ab , Acb , and Ad . But when B moves up to A , the $\angle bAd$ ($= \angle BAD$) will, by *Lem. 6*, ultimately vanish; $\therefore Ab$, and also the intermediate arc Acb , will continually approach Ad , and at length will ultimately coincide with, and become equal to it; and consequently AB , ACB , and AD , which are always proportional to these, will also ultimately be to each other in a R° . of equality,

Notes to Lemma 7.

37. In the demonstration B D is supposed to move parallel to itself, as B moves up to A, while bd remains fixed. Hence (1) by the motion of B towards A, $A b$ is continually approaching nearer to A d without limit; while, at the same time, it carries the intermediate arc $A c b$ (which is continually unbending itself) along with it. (2) The *magnitudes* of $A b$ and $A c b$ also continually approach to that of A d , nearer and nearer without limit; though these quantities can never exceed A d , nor indeed equal it, till B and A actually coincide; \therefore the *finite* lines $A b$, $A c b$, and A d ultimately coinciding are equal; whence this is also inferred of the *vanishing* lines A B, A C B, and A D, which are always proportional to them.

38. The Lemma is frequently explained by supposing R B D (*Fig. 3*) to move round R fixed as a centre, while, by this revolution, B continually approaches to A; at the same time dr moves round the fixed point d in a contrary direction, so as always to keep parallel to R B D. But this explanation is clearly at variance with Newton's notions, as is evident from the next Lemma.—See Art. 41.

39. Since it would be difficult for the understanding, in contemplating quantities, which elude the notice of the senses, clearly to perceive the changes which take place in the vanishing chord, arc, and tangent, and the limit to which their proportions continually approach, Newton has had recourse to the artifice of substituting, in the room of these *vanishing* quantities, *finite* ones, which bear a constant proportion to the others; and by ascertaining the limit which the R° . between the latter ultimately attains, on the coincidence of B and A, he discovers also the limit of the Ratios of the vanishing quantities, which are proportional to them. The same observation is applicable to the 8th and 9th Lemmas.

LEMMA VIII.

40. Produce AD to any distant point d , and draw $db r$ parallel to DBR , meeting AB and AR produced in b and r ; and through b describe the curve $Ac b$ always similar to ACB ; then the figures RAB , $RACB$, and RAD are always similar to rAb , $rAc b$, and rAd ; they are likewise always proportional to them. For $RAB : rAb :: RA^2 : rA^2 :: RAD : rAd$; $\therefore RAB : RAD :: rAb : rAd$; also sector $RACB$: sector $rAc b :: RA^2 : rA^2$ (Lemma IV.) $\therefore RAD : rAd$; $\therefore RACB : RAD :: rAc b : rAd$. Now let B move up to A , and ultimately coincide with it, then the $\angle dAb$ ($= \angle DAB$) will ultimately vanish; \therefore the three continually finite $\Delta^s rAb$, $rAc b$, and rAd will ultimately coincide with each other, and consequently be ultimately similar and equal to each other; \therefore also the vanishing $\Delta^s RAB$, $RACB$, and RAD , which are always proportional to the former, will also be ultimately similar and equal to each other.

Note to Lemma 8.

41. It is plain, from the words "*triangula tria semper finita*," in this Lemma, that RBD is supposed to move parallel to itself, while $db r$ remains fixed; and not that RBD moves round R as a fixed point; for in the latter case the $\Delta^s rAb$, $rAc b$, rAd would be ultimately infinitely great, and the purpose for which these last Δ^s were introduced (see Art. 39) thus rendered useless.

LEMMA IX.

42. Produce AE to any distance point e , and take

$Ae : Ad :: AE : AD$; draw ec, db parallel to EC, DB , and let them meet the chords AC, AB produced in c, b ; then the $\triangle Adb, Aec$ being similar to ADB, AEC respectively; $Ab : AB (:: Ad : AD :: Ae : AE) :: Ac : AC$; $\therefore c, b$, will be in the curve Abc , which is similar to ABC ; in the same manner during the approach of C and B to A , the points b, c , determined in like manner, will always be found in a curve similar to ABC ; and because the curves Abc, ABC are similar, the areas, Abd, Ace will be similar, to the areas ABD, ACE respectively, and they are \therefore proportional to each other respectively; for $ABD : Abd (:: AD^2 : Ad^2 :: AE^2 : Ae^2) :: ACE : Ace$; \therefore altern o . $ABD : ACE :: Abd : Ace$. To the similar curves ABC, Abc draw the tangent $AFGfg$; then as C and B move up to A , and ultimately coincide with it, the $\angle cAg$ is continually diminished and will ultimately vanish, \therefore the curvilinear areas Abd, Ace will ultimately coincide with the rectilinear areas Afd, Age ; and be \therefore ultimately to each other as $Ad^2 : Ae^2$; \therefore also will the curvilinear areas ABD, ACE , which are proportional to these others, be also ultimately in the Ratio of $Ad^2 : Ae^2$ or of $AD^2 : AE^2$.

Note to Lemma 9.

43. It may be observed here, that the \angle , which EA makes with the curve, as indeed all *determined* \angle^s , and quantities of whatsoever kind in this and the following Sections, are supposed to be finite; Newton disclaims the use of infinitely small *determinate* quantities as unintelligible, and by the words infinitely small \angle^s , or infinitely small quantities, he means *variable* quantities, which by a continual flux are decreasing without limit.

LEMMA X.

Introductory Article to Lemma 10.

44. *If the abscissæ A B, A D (Fig. 28,) be as the times in which a body, urged by any finite force, describes two spaces; and the ordinates B C, D E be as the velocities generated in those times; and if A C E be the curve traced out by the extremities of these ordinates, the areas A B C, A D E will be as the spaces described.*

Let the times be divided into any number of equal parts A F, F G, G H, &c., and complete the parallelograms A K, F L, G M, &c.; then if the force be supposed to act only at equal intervals of time, so as to make the body move uniformly during the times A F, F G, G H, &c. with the velocities F K, G L, H M, &c., the spaces described in these times will be represented by the parallelograms, and the sums of the spaces by the sums of the parallelograms. Now let the intervals of time be continually diminished, then will the force, which now acts by impulses, continually become nearer and nearer a force acting incessantly; and the sums of the parallelograms, which represent the spaces, continually approach nearer and nearer to the curvilinear areas, till at length, when the intervals of time are diminished, and their number increased in infinitum, the force will become an incessant force, and at the same instant the sums of the parallelograms become = the curvilinear areas (Lem. II.); \therefore under the circumstances mentioned in the Proposition, the spaces will be accurately measured by the curvilinear areas.

We may observe that in this, and Propositions of the like nature, a false hypothesis is made, viz. that the force acts by impulses, and by consequence we deduce a false conclusion, viz. that the spaces are

represented by the sums of the parallelograms; but as the assumed hypothesis approaches to the true, so does the false conclusion approach to the true conclusion; till at length, upon the attainment of the true hypothesis, we attain at the same time the true conclusion: the true hypothesis and true conclusion being respectively the limits of the assumed hypothesis, and the conclusion consequent upon it.

Lemma 10.

45. Let the times be represented by the lines AD , AE , and the velocities generated, by the ordinates DB , EC , then the spaces described with these velocities will, by what has been just proved, be represented by the areas ABD , ACE described by these ordinates; but the prime R° of these nascent areas ABD , ACE is (Lem. IX.) that of $AD^2 : AE^2$; *i. e.* the spaces described are, in the very beginning of the motion, in the duplicate R° of the times in which they are described.

Note to Lemma 10.

46. Observe that Newton here says the force must be a *finite* one; and that it must be so is evident from hence, that if it were indefinitely small, the curve AB would make with AD an indefinitely small \angle , and \therefore Lemma 9, where this \angle is supposed *finite*, would be inapplicable.

Lem. 10.—Cor. 1.

47. Let AB and ab (*Fig. 30*) be similar parts of similar figures described by two bodies in proportional times; and let two equal forces similarly applied act upon the bodies, sufficient to make them move from B to C , and from b to c , in the time that they would have described AB , ab ; then they will describe two other curves AC , ac ; and the limiting R° of $BC : bc$ (which, as being the distances the bodies have

erred from their former course, are called errors in this Corollary) will be that of the squares of the times in which $A B$, $a b$ would have been described. For $B C$, $b c$ may be considered as spaces described from rest in those times by equal forces, and \therefore the Lemma is applicable to them.

Note to Lemma 10.—Cor. 1.

48. "Are nearly, &c."—Though strictly speaking, by the spaces mentioned in this Lemma are meant not any spaces actually described, however small they be taken, but only the limiting ratio of the spaces; yet still if $B C$, $b c$ be *actual* spaces described, provided they are sufficiently small, they will be as the square of the times quam proxime, *i. e.* without any sensible error; and thus this and the next Corollary are applied in the 66th Proposition to find the errors produced in the motions of the moon, &c. by the attraction of the sun.

Lemma 10.—Cor. 3.

49. Let $A D$, $a d$ (*Fig. 29*) represent two equal times, $D B$, $d b$ the velocities generated in those times; then will the spaces be represented in the two cases by $A D B$, $a d b$; but $A D B : a d b :: A D \times D B : a d \times d b$ ultimately, $\therefore D B : d b$ ultimately (since $A D = a d$); *i. e.* in the very beginning of the motion, space described varies as the momentary increment of velocity when the time is given; but the velocities generated in an indefinitely small given time are proper measures of the accelerating forces; \therefore in the very beginning of the motion, space varies as force, when time is given; but (by Lemma) space varies as T^2 , when force is given, \therefore when neither are given, the space will, in the very beginning of the motion, vary as $F \times T^2$.

LEMMA XI.

Introductory Articles to Lemma 11.

50. Any two arcs of curve lines touch each other when the same right line is the tangent of both at the same point; but when they are applied upon each other they never perfectly coincide, unless they are similar arcs of equal and similar figures; and the curvature of lines admits of an indefinite variety. Because the curvature is uniform in a given \odot , and may be varied at pleasure in them, by enlarging or diminishing their diameters, the flexure or curvature of circles serves for measuring that of other lines.

51. As of all the right lines, that can be drawn through a given point in the arc of a curve, that is the tangent which touches the arc so closely, that no right line can be drawn between them; so of all the circles that touch a curve in any given point, that is said to have the *same curvature* with it, which touches it so closely that no \odot can be drawn through the point of contact between them; all other circles passing either within or without them both. This \odot is called the \odot of curvature belonging to the point of contact. The arc of this \odot cannot coincide with the arc of the curve, but it is sufficient to denote it the \odot of curvature that no other \odot can pass between them; as the tangent of the arc of a curve cannot coincide with it, but is applied to it so that no right line can be drawn between them. As in all curvilinear figures the position of the tangent is continually varying, so the curvature is continually varying in all curvilinear figures, the \odot only excepted. As the curve is separated from its tangent by its flexure or curvature, so it is separated from its \odot of curvature in consequence of the encrease or decrease of its curvature: and as its curvature is greater or less, according as

it is more or less inflected from the tangent, so the variation of curvature is greater or less, according as it is more or less separated from the \odot of curvature. It is manifest that there is but one \odot of curvature belonging to an arc of a curve at the same point; for if there were two such circles, any circles described between these through that point would pass between the curve and \odot of curvature, against the supposition. Having thus shewn what the \odot of curvature is, it will be necessary to point out, in the next place, the method of describing it; this is done by the following proposition:—

52. *Let E M H (Fig. 31) be any curve, E T a tangent at the point E, E B b a right line, making any \angle with E T; T M R any straight line parallel to E B, meeting the tangent in T, and the curve in M; then if the rectangle $M T \times T K$ be always taken $= E T^2$, and F K B be the curve traced out by the point K thus taken, and if this curve ultimately passes through B, the circle whose chord is E B, and tangent E T, shall have the same curvature with the curve E M H at the point E; and the contact of E M and E R shall be always the closer, the less the \angle is, that is contained at B by the curve B K F, and the circle of curvature B Q E.*

Let T K meet the \odot in R and Q; then $R T \times T Q = E T^2 = M T \times T K$ (by hypothesis) $\therefore R T : M T :: T K : T Q$. Suppose first that B K, the part of the curve B K F that is next to the point B adjoining to it, falls without the \odot B Q, and suppose T K, by moving parallel to itself, to approach to E B till it coincide with it; then while the point K describes K B, T K being greater than T Q, R T must be greater than M T, and the arc E M of the curve must pass without the \odot E R, betwixt it and the tangent E T; and since any \odot described through E, upon a chord less than E B touching E T, falls within the \odot E R B, it is manifest that no such \odot

can pass betwixt the curve EM and $\odot ERB$. Nor can any $\odot Erb$ described upon a chord Eb greater than EB touching ET pass between ER and EM ; for let TK meet this \odot in r and q , then $rT \times Tq = ET^2 = MT \times TK$; $\therefore MT : rT :: Tq : TK$, and since FKB (by hypothesis) passes through B so that the part of it, that is next adjoining B , must be within the arc bq of the $\odot bqE$, it follows that while K describes this part of FKB , Tq must be greater than TK ; and $\therefore MT$ greater than rT . Therefore the arc Er of the $\odot Erb$ is without the curve EM , and passes betwixt it and the tangent ET . Hence no \odot whatever can pass betwixt EM and ER ; and consequently the $\odot ERB$ has the same curvature with EM at E . Suppose now that the part of the curve BKF , that is next adjoining to B , falls within BQ (*Fig. 31*); then while K describes this part of the curve FKB , TK being less than TQ , RT must be less than MT , and the arc EM must fall within ER ; and since any \odot described through E , upon a chord greater than EB , falls without the $\odot ER$, it is manifest that no such \odot can pass betwixt ER and EM . Nor can any $\odot Erb$ described upon a chord Eb less than EB touching ET , pass between ER and EM ; for let TK meet this \odot in r and q , and MT being $: rT :: Tq : TK$, and Tq being less than TK while K describes KB , MT must be less than rT ; and consequently the arc Er must fall within EM . Therefore, in either case, all the circles that can be described through E fall without both ER and EM , or within them both; and no \odot whatever can pass between them when the rectangle $MT \times TK$ is always $= ET^2$, and the curve in which K is always found passes through B ; *i. e.* the $\odot ERB$ and the curve EM have the same curvature at E , which was the first part of the proposition.

Let Em (*Fig. 32*), any other curve touching ET in E , and fkb , another curve passing through B ,

meet TK in m and k ; and let the rectangle $mT \times Tk$ be likewise always $= ET^2$; then the curvature of Em at E shall be the same as that of the $\odot ERB$, or that of the curve EM , by what has been demonstrated. Because $mT \times Tk$, $MT \times TK$, $RT \times TQ$ are equal to each other, $Tm : TM :: TK : Tk$ and $Tm : TR :: TQ : Tk$. Therefore if the arc Bk pass between BK and BQ , the curve Em must pass between EM and ER so that Em must have a closer contact with this \odot , than EM has with it: and the less the \angle is, that is formed by the curve FKB and the \odot of curvature EQB at B , the closer is the contact at E of the curve EMH , and the \odot of curvature EQB . Thus the curve BKF , by its intersection with EB , determines the curvature of EM ; and by the \angle in which it cuts the \odot of curvature it determines the degree of contact of EM and that \odot ; the $\angle BET$ and the right line ET being given.

Cor. 1. Since $MT \times TK = ET^2$, $TK = \frac{ET^2}{MT}$. Now let M move up to E and coincide with it, then will TK ultimately coincide with, and be equal to, EB ; \therefore in all cases, whatever be the curve, the chord of the \odot of curvature $=$ the ultimate value of $\frac{ET^2}{MT}$, or $=$ the ultimate value of $\frac{EM^2}{MT}$.

Cor. 2. It appears from the demonstration, that according as the arc BK falls without or within the arc BQ , the arc EM falls without or within the $\odot ERB$; that when the curve FKB cuts the $\odot ERB$ in B , the curve HME cuts the \odot of curvature in E ; that when the curve FKB is on the same side of the $\odot BQE$ on both sides of B , the curve HME , continued on both sides of E , is on the same side of the \odot of curvature; and that the contact of the curve EMH and the \odot of curvature is closest when the curve BK touches the arc BQ in B , the $\angle BET$

being given ; but is farthest from this, or is most open, when B K touches the right line E B in B.

Cor. 3. There may be indefinite degrees of more and more intimate contact between a \odot E R B and a curve E M H. The 1st degree is when the same right line touches them both in the same point ; and a contact of this sort may take place betwixt any \odot , and any arc of any curve. The 2d is when the curve E M H and \odot E R B have the same curvature, and the tangents of the curve B K F and \odot B Q E intersect each other at B in any assignable angle. The contact of the curve E M and \odot of curvature E R at E is of the 3d degree or order, and their osculation is of the 2d, when the curve B K F touches the \odot B Q E at B, but so as not to have the same curvature with it. The contact is of the 4th degree or order, and their osculation of the 3d, when the curve B K F has the same curvature with the \odot B Q E at B, but so as that their contact is only of the 2d degree : and this gradation of more and more intimate contact, or of approximation towards coincidence, may be continued indefinitely ; the contact of E M and E R at E being always of an order two degrees closer than that of B K and B Q at B. There is also an indefinite variety comprehended under each order. Thus when E M and E R have the same curvature, the \angle formed by the tangents of B K and B Q admits of indefinite variety, and the contact of E M and E R is the closer the less that \angle is. And when that \angle is of the *same* magnitude, the contact of E M and E R is the closer the greater the \odot of curvature is ; for since $TR : TM :: TK : TQ$, div^o. RM (which subtends the \angle of contact M E R) : $TR :: KQ : TK$, and $\therefore RM : KQ :: RT \times TQ (ET^2) : KT \times TQ$; \therefore when ET is given,

RM varies as $\frac{KQ}{KT \times TQ}$, and when K Q (or \angle K B Q) is given, RM is less, in proportion as

the rectangle $K T \times T Q$, which ultimately = ch. curv.³, is greater. When $B K$ touches the \odot $B Q$ at B , it may touch it on the same or on different sides of their common tangent; and the \angle of contact $K B Q$ may admit of the same variety with the \angle of contact $M E R$ in the former case. But there is seldom occasion for considering these higher degrees of more intimate contact of the curve $E M H$, and \odot of curvature $E R B$.

Cor. 4. The curvature is uniform in the \odot only. When the curvature of $E M H$ encreases from E towards H , and consequently corresponds to that of a \odot gradually less and less, the arc $E M$ falls within $E R$, and $B K$ is within $B Q$. When the curvature of $E M$ decreases from E towards H , and consequently corresponds to that of a \odot that is gradually greater and greater, the arc $E M$ falls without $E R$, and $B K$ is without $B Q$. According as the curvature of $E M$ varies more or less, it is more or less unlike to the uniform curvature of a \odot , the arc of the curve $E M H$ separates more or less from the arc of the \odot of curvature $E R B$, and the \angle contained by the tangents of $B K F$ and $B Q E$ at B is greater or less. And thus the *quality* of curvature, (as it is called by Sir I. Newton) depends on the \angle contained by the tangents of $B K$ and $B Q$ at B .

Cor. 5. Let the curve $E M H$, for example, (*Fig. 33*) be a parabola, $E B$ a diameter, $E T$ the tangent at E , then because parameter $\times T M = E T^2 = M T \times T K$, $T K$ is always = the parameter, \therefore in this case $B K$ is a straight line parallel to the tangent $E T$, which intersects $E B$ in B , so that $E B$ is = that parameter. Therefore if upon the diameter of a parabola, a right line $E B$ be taken from E the vertex of this diameter = to its parameter, a \odot $E R B$, described upon this right line as its chord, that touches the parabola at E , shall be the \odot of curvature. And because the right line $B K$ cuts the \odot $B Q E$ in B , unless when E is the vertex of the figure, the parabola

cuts the \odot of curvature (that case excepted); and passes within the \odot of curvature when it is produced towards the vertex, but without it when produced the contrary way.

Cor. 6. When EB does not meet with the curve FK (*Fig. 34*), but is its asymptote; any \odot being described touching ET in E , a greater \odot shall always pass between it and the curve EM ; and the greater this \odot is, the closer shall its contact be with the curve EM . For since the curve FK produced passes without any \odot EQB , how great soever, that can be described through E , EM must always pass betwixt ER and the tangent ET . This is the case in which the curvature is said to be infinitely small, (being less than that of any \odot) or the radius of curvature infinitely great. Of this we have an example in the vertex of the cubical parabola; for in that case $ET^3 = TM \times a^2$ (where a^2 is a given square) $\therefore \frac{ET^3}{TM} = a^2$, but $\frac{ET^2}{TM} = TK$, $\therefore \frac{ET^3}{TM} = TK \times ET$, hence $ET \times TK =$ the given square a^2 ; \therefore the curve FK is the common hyperbola, whose asymptotes are EB and ET . The curvature is of the same kind at the vertex of any parabola, wherein TM is as any power of ET , whose exponent exceeds 2; for FK , in all those cases, is an hyperbola, of which EB is an asymptote.

Cor. 7. When the curve FK (*Fig. 35*) passes through E , no \odot can be described through E so small, but a less \odot shall pass between it and the curve EM , and the less this \odot is, the closer shall its contact with EM be. For since the curve FK passes within any \odot that can be described through E on the same side of ET , the arc EM is always within ER . In this case, because the curvature surpasses that of any \odot , it is said to be infinitely great, or the radius of curvature to be infinitely small. Of this we have an example at the vertex or cuspid of the semi-

cubical parabola; for in that case $ET^3 = MT^2 \times a$, (where a is a given line) $\therefore \frac{ET^3}{MT^2} = a$, and $\frac{ET^4}{MT^2} = a \times ET$; but $\frac{ET^2}{MT} = TK$, $\therefore \frac{ET^4}{MT^2} = TK^2$, hence $a \times ET = TK^2$; $\therefore FKE$ is the common parabola, whose *latus rectum* $= a$, and which touches EB in E .

Lemma 11.

53. *Case 1.* It follows, from Cor. 1. Art. 52, that if AG , drawn perpendicular to AD , and BG , perpendicular to AB , intersect each other in G , the limit to AG is the chord of curvature AI . For by similar $\triangle^s G A : AB :: AB : BD$, $\therefore GA = \frac{AB^2}{BD}$, and consequently their limits are equal; but

the limit of $\frac{AB^2}{BD}$ is the chord of curvature (by Cor.

1), \therefore also the ultimate value of AG is the chord of curvature, or AG ultimately $= AI$. The proof of the Lemma is \therefore evident.

Case 2. Let BD and bd (*Fig. 36*) be equally inclined to AD at any given \angle ; draw BE , be perpendicular to AD , then by similar $\triangle^s BD : bd :: BE : be$; *i. e.* in the given R^o of $AB^2 : Ab^2$ by the first case.

Case 3. Let the \angle^s at D and d (*Fig. 36*) be not equal, *i. e.* let BD , bd converge to some point O , at a finite distance. Draw BE , be perpendicular to AD , then when AB , Ab are diminished without limit, their difference Bb will be diminished without limit; \therefore the $\angle BOb$ will be diminished without limit; but $\angle BOb = \angle A d O - \angle A D O$; \therefore the $\angle A d O = \angle A D O$ ultimately, and consequently $BD E$, $b d e$ are ultimately similar, and BD

$\therefore b d :: B E : b e$; *i. e.* in the ultimate R^o of $A B^2 :: A b^2$.

Lemma 11.—Cor. 2.

54. Let the sagittæ EF , ef (*Fig. 37*) bisecting the chords AB , Ab , meet in H ; join AH and produce it to K , making $AH = HK$; join KB , Kb and produce them to D , d . By construction $AH :: AK :: AF : AB$, $\therefore HF$, KB or FL , BD are parallel. When B moves up to A , the ultimate R^o of $EL : BD$ is that of $AE^2 : AB^2$ (by Lem.) or that of $AF^2 : AB^2$ or that of $1 : 4$ (for AF , AE are ultimately equal). But $BD : FL :: AB : AF :: 4 : 2$, $\therefore EL : FL$ ultimately $:: 1 : 2$, consequently FE , EL are ultimately equal, and $\therefore EF$ is ultimately to $BD :: 1 : 4$. In like manner ef is ultimately to $bd :: 1 : 4$; $\therefore EF : BD :: ef : bd$ ultimately, and $EF : ef :: BD : bd$ ultimately; but BD , bd converge to a given point K , \therefore (Lem. Case 3), the points B , b meeting in A , BD , bd and consequently EF , ef are ultimately as the squares of AB , Ab .

Lemma 11.—Cor. 5.

55. By Cor. 1, $AC : Ac :: CB^2 : cb^2$ ultimately, (*Fig. 38*) which is the property of the parabola; \therefore the curve AB , whatever be its nature, provided it be of finite curvature (see Schol.) may ultimately be considered as a parabola; \therefore the curvilinear area $ACB = \frac{2}{3} CD$ ultimately, and consequently the curvilinear area $ADB = \frac{1}{3} CD$ ultimately $= \frac{2}{3}$ of the $\triangle ADB$ ultimately, and consequently the remainder, the segment AB , $= \frac{1}{3} \triangle ADB$ ultimately; but $\triangle ADB$ varies as AD^3 or AB^3 ultimately (Cor. 4); \therefore also the curvilinear area ADB and segment AB vary as AD^3 or AB^3 ultimately.

SCHOLIUM.

Introductory Articles to Scholium.

56. Prop. 1. *Let there be two curves of any kind (Fig. 39) A B, A b, and suppose the \angle of contact B A D in the 1st case to be indefinitely greater than the \angle of contact b A D in the other; then shall the curvature of A B be indefinitely greater than that of A b; and conversely.*

Let A I, A i be the diameters of curvature of A B and A b respectively; then $A I = \frac{A D^2}{B D}$ ultimately,

and $A i = \frac{A D^2}{b D}$ ultimately, $\therefore A I : A i$ in the ul-

timate R° . of $\frac{A D^2}{B D} : \frac{A D^2}{b D}$, i. e. in the ultimate R° .

of $b D : B D$. Now the \angle B A D is indefinitely greater than $b A D$ by hypothesis, but the ultimate R° . of $B D : b D$ is the same with that of those \angle 's, for they ultimately measure them; \therefore ultimately B D is indefinitely greater than $b D$; \therefore A i is also indefinitely greater than A I; but the curvature \propto

$\frac{1}{D^r \text{ of curv}^e}$; \therefore the curvature of A B is indefinitely

greater than that of A b.

Next let the curvature of A B be indefinitely greater than that of A b, then shall the \angle B A D be indefinitely greater than the \angle b A D; for as before $A I : A i$ in the ultimate R° . of $b D : B D$, and A i is indefinitely greater than A I by hypothesis, \therefore B D is ultimately indefinitely greater than $b D$, and consequently the \angle B A D indefinitely greater than the \angle b A D.

57. Prop. 2. *Let there be two curves A B, A b, and let the \angle of contact B A D bear a finite Ratio to the \angle of contact b A D; then if the curvature of A B be finite, the curvature of A b will also be finite; and conversely if the curvature of A B, A b be both finite, the \angle^s of contact B A D, b A D will be to each other in a finite Ratio.*

For, as before, A I : A i in the ultimate R° . of b D : B D; but b D : B D ultimately in a finite R° . by hypothesis, \therefore A I : A i in a finite R° ., but A I is finite, \therefore also A i is, and consequently curvature of A b is finite.

Again A I : A i in the ultimate R° . of b D : B D; but the R° . of A I : A i is finite by hypothesis \therefore the ultimate R° . of b D : B D, and consequently that of the \angle^s of contact, is finite.

Cor. 1. Let A B be any \odot , then since the curvature of a \odot is always finite, it is manifest that the curvature of all curves, whose \angle^s of contact bear a finite R° . to that of this \odot ; or, which is the same thing, the subtenses of whose \angle^s of contact bear ultimately a finite R° . to that of this \odot , will be finite; and if the limiting R° . of the subtenses of the \angle of contact of the curve and \odot be not only finite, but also a R° . of equality, then the curve and \odot have the same curvature at the point of contact.

Cor. 2. Since A I : A i :: $\frac{1}{B D} : \frac{1}{b D}$, the curvatures of two curves are to each other as the \angle^s of contact, or as the *ultimate* subtenses of these angles.

Scholium.

58. In the above Lemma, the \angle of contact is supposed to bear a finite R° . to that of a \odot , *i. e.* the curvature is supposed to be neither indefinitely great, nor indefinitely small (Cor. 1. Art. 57.) This is

manifest from the Lemma itself, which was proved on the supposition that the diameters AG , $A\bar{g}$ had a limit, viz. AI ; *i. e.* that the curve had a \odot of curvature. To shew, however, this in another point of view, it may be worth while to prove (1) That, conversely to the Lemma, if BD vary as AD^2 ultimately, the curvature of AB is finite. (2) That if BD ultimately vary in any other R° . greater or less than that of AD^2 , the curvature is not finite, but infinitely small or infinitely great. (3) That there may be curves, whose curvatures are indefinitely great or indefinitely small, and again curves, whose curvatures are indefinitely greater or indefinitely smaller than that of those others, and so without end; and thus that the \angle of contact BAD may be divided into a series of \angle 's, each of which is indefinitely greater or indefinitely smaller than the one which is adjacent to it, and that this division may be continued *sine limite*.

(1) Let AEV (*Fig. 40*) be any \odot , and AB the curve, then since BD ultimately varies as AD^2 (by hypothesis) it ultimately $= \frac{AD^2}{a}$ (where a is a

proper constant quantity), but ED ultimately $= \frac{AD^2}{AV}$, \therefore the ultimate R° . of $BD : ED =$ that of

$\frac{AD^2}{a} : \frac{AD^2}{AV} =$ that of $AV : a$, which last R° . is

always finite, whatever be the value of AV provided it be finite, and \therefore the ultimate R° . of $BD : ED$ is finite, and \therefore the curvature of AB is finite, (by Cor. 1, Art. 57.)

(2) Let BD (*Fig. 41.*) ultimately vary in any R° . greater, than that of AD^2 , for instance AD^3 , then

BD ultimately $= \frac{AD^3}{a^2}$ (where a is a proper constant quantity), also as before ED ultimately $=$

$\frac{A D^2}{A V}, \therefore B D : E D :: \frac{A D^3}{a^2} : \frac{A D^2}{A V}$ ultimately, *i. e.*

$:: A D : \frac{a^2}{A V}$ ultimately, but in the ultimate state

$A D$ is indefinitely less than $\frac{a^2}{A V}$, whatever be the value of $A V$ provided it be finite, $\therefore B D$ is ultimately indefinitely less than $E D$; and \therefore the curvature of $A B$ is indefinitely small, (by Art. 56.) *i. e.* no \odot however great, can pass between the curve $A B$ and tangent $A D$, as appeared also from Cor. 6, Art. 52. And the same may be shewn when $B D$ ultimately varies as $A D^4, A D^5, A D^6, \dots, A D^n$, where n (provided it be greater than 2) may be any N^o . whatever, whole or fractional.

Next let $B D$ (*Fig. 40*) ultimately vary in any R^o . less than that of $A D^2$, for instance $A D^{\frac{1}{2}}$. then $B D$ ultimately $= \frac{A D^{\frac{1}{2}}}{a^{\frac{1}{2}}}, \therefore B D : E D :: \frac{A D^{\frac{1}{2}}}{a^{\frac{1}{2}}} : \frac{A D^2}{A V}$ ultimately, *i. e.* $:: \frac{A V}{a^{\frac{1}{2}}} : A D^{\frac{1}{2}}$ ultimately ;

but in the ultimate state, $A D^{\frac{1}{2}}$ is indefinitely less than $\frac{A V}{a^{\frac{1}{2}}}$, whatever be the value of $A V$ provided it

be finite; $\therefore E D$ is ultimately indefinitely less than $B D$, and \therefore the curvature of $A B$ is indefinitely great; *i. e.* there can be no \odot , however small, which does not pass without the curve (by Art. 56); as appeared also from Cor. 7, Art. 52. And the same may be shewn when $B D$ ultimately varies as $A D^{\frac{4}{3}}, A D^{\frac{5}{3}}, A D^{\frac{6}{3}}, \dots, A D^n$, where n (provided it be less than 2) may be any fractional N^o . whatever.

(3) (*j*) Let $A P$ (*Fig. 42*) be a curve, such that

D P ultimately varies as $A D^3$, then, as we have seen above, the curvature of A P is indefinitely small.

(j) Again, let A C be another curve, such that C D ultimately varies as $A D^4 =$ ultimately $\frac{A D^4}{m^3}$,

$\therefore P D : C D :: \frac{A D^3}{a^2} : \frac{A D^4}{m^3} :: \frac{m^3}{a^2} : A D$ ultimately, but A D is ultimately indefinitely less than $\frac{m^3}{a^2}$, $\therefore C D$ is ultimately indefinitely less than P D,

or curvature of A C is indefinitely less than that of A P, which is indefinitely small. And in the very same manner, if the subtense ultimately varies as $A D^5$, $A D^6$, &c., we shall have a series of \angle^s of contact going on in infinitum; each of which is indefinitely less than the preceding. Also between any two of these \angle^s there may be inserted a series of intermediate \angle^s going on in infinitum, any one of which is indefinitely less than the preceding. For instance, between $A D^2$ and $A D^3$ there may be inserted the series $A D^{\frac{13}{6}}$, $A D^{\frac{11}{5}}$, $A D^{\frac{9}{4}}$, $A D^{\frac{7}{3}}$, $A D^{\frac{5}{2}}$,

$A D^{\frac{11}{4}}$, $A D^{\frac{14}{5}}$, &c. &c. And again, between any two \angle^s of this series, there may be inserted a new series of intermediate \angle^s , differing from each other by infinite intervals, and so on without limit.

Next (j) let A E be a curve, such that E D ultimately varies as $A D^{\frac{4}{3}}$, then, as has been before shewn, the curvature of A E is indefinitely great.

(j) Again, let A F be another curve, such that F D ultimately varies as $A D^{\frac{4}{3}} = \frac{A D^{\frac{4}{3}}}{m^{\frac{1}{3}}}$ ultimately,

then $F D : E D :: \frac{A D^{\frac{4}{3}}}{m^{\frac{1}{3}}} : \frac{A D^{\frac{3}{2}}}{a^{\frac{1}{2}}} : \frac{a^{\frac{1}{2}}}{m^{\frac{1}{3}}} : A D^{\frac{1}{2}}$ ul-

timately, but $A D^{\frac{1}{2}}$ is ultimately indefinitely less than $\frac{a^{\frac{1}{2}}}{m^{\frac{1}{2}}}$; \therefore ultimately $F D$ is indefinitely greater than $E D$, or curvature of $A F$ is indefinitely greater than that of $A E$, which is indefinitely great. And in the very same manner, if the subtense varies as $A D^{\frac{5}{4}}$, $A D^{\frac{6}{5}}$, $A D^{\frac{7}{6}}$,..... $A D^n$, (n being any fractional number whatever less than 2) we shall have a series of \angle^s of contact running on in infinitum, each of which is indefinitely greater than the one which precedes it. "Neque novit natura limitem."

NOTES TO SECTION II.

Introductory Articles to Section II.

59. *Defn.* 'Whatever tends constantly to solicit or impel a body towards a fixed point or centre, is called a *centripetal force*.'

The centripetal force, which is found to exist in the sun and planets, is, by way of distinction, called *gravity*, or the *force of gravity*.

60. The word *gravity* is used in three different senses, or rather it is spoken of as being greater or less in reference to three different measures. As (1) we may say for instance that the gravity of the earth, at the distance of one mile from its surface, is greater than the gravity of the earth, at the distance of 1000 miles from its surface. By this proposition we mean that the *velocity* uniformly generated in a given time, in a body at one mile's distance from the earth's surface, is greater than the velocity uniformly generated in the same given time, at the distance of 1000 miles from it. The word, when used in this sense, is called the accelerating force of gravity; and, in general, when we speak of the force of gravity at different distances from the same attracting body, the accelerating force of gravity is always understood. Hence the following definition. 'When the velocity uniformly

produced in a given time is the measure by which gravity is said to be greater or less; then it is called the *accelerating force of gravity*.'

This accelerating force of gravity is in all cases found to be invariably the same at equal distances from the centre of the same attracting body, and to vary according to some regular law of the distance from that centre; and hence it is, that the variation of this force is usually expressed in terms of the distance from the centre of the attracting body; for instance, when it is said that gravity varies as the n^{th} power of the distance, the expression denotes that the accelerating force of gravity (measured by the velocity uniformly generated in a given time) increases or decreases as the n^{th} power of the distance from the centre increases or decreases; and $F \propto D^n$ is called the law of the accelerating force.

(2) Again, we may say that the gravity exerted upon a cubic inch of gold is greater than that upon a cubic inch of cork. Here we no longer refer to the same measure as before, but mean by the Prop. that the *quantity of motion*, uniformly generated in a given time in the gold, is greater than that uniformly generated in the same time in the cork, when placed at an *equal* distance from the attracting body's centre; or, in other words, that the weight of the gold is greater than the weight of the cork. The word, when used in this second sense, is called the *motive force of gravity*, and as, when speaking of gravity at different distances from the centre of the same attracting body, we mean the accelerating force of gravity; so, when speaking of the gravity exerted upon different bodies at the same distance, the motive force of gravity is to be understood. Hence the following definition. 'When gravity is considered as greater or less in proportion to the quantity of motion it uniformly produces in a given time, then it is called the *motive force of gravity*.'

The only difference then betwixt the accelerating

and motive force of gravity is this, that inasmuch as gravity produces both velocity and momentum, we call it one or the other, according, as for the sake of convenience, the velocity or momentum is taken to be the measure of it.

(3) Lastly, we frequently speak of the gravity of different attracting bodies, as when we say that the gravity of the earth is greater than the gravity of the moon. By this Prop. it is meant that the accelerating force of the earth, at a given distance from its centre, is greater than the accelerating force of the moon at the same given distance from *its* centre. The word, when used in this last sense, is called the absolute force of gravity; and when the gravity of different attracting bodies is spoken of, the absolute force of gravity (measured in the manner above described) is always understood. Hence the following definition. 'When gravity is considered as greater or less, in reference to the efficacy of the cause which produces it, then it is called the *absolute force of gravity*.'

61. *The accelerating forces, acting upon bodies, at different distances from different centres of force, are as the absolute forces, and the law of the force jointly; i. e. if Φ and ϕ represent the absolute forces, D and δ the two distances, and the law of the force be the direct n^{th} power of the distance; $F : f :: \Phi \times D^n : \phi \times \delta^n$.*

For if the distances of the two bodies from their respective centres be the same, the accelerating forces are the same with the absolute forces, i. e. if $D = \delta$; $F : f :: \Phi : \phi$; and if the absolute forces be the same, i. e. if $\Phi = \phi$; $F : f :: D^n : \delta^n$; \therefore when both the absolute forces and distances are different, $F : f :: \Phi \times D^n : \phi \times \delta^n$.

62. *Cor.* If f , ϕ , and $\delta = 1$; F will be represented by $\Phi \times D^n$, or by the absolute force and the law of the force.

PROPOSITION I.

Note to Prop. 1.

63. Since (*Fig. 43*) the Δ^s SAB , SBc , Scd , &c. are always equal to each other, and to the Δ^s SAB , SBc , Scd , &c. the whole $SABd$ is equal to the whole polygon $SABCD$, and their limits will be equal; but the limiting position of ABd is that of a tangent at A , and the limit of the polygon $SABCD$ is the curvilinear area $SABCD$; if $\therefore Ad$ (*Fig. 44*) be the space described in the tangent with the velocity at A continued uniform, in the time that the body describes AD with a variable velocity, the area SAd will be equal to the area SAD .

Note to Prop. 1.—Cor. 1.

64. If the areas described in a given time are not equal, *i. e.* if bodies move in different orbits, the bases of the Δ^s , which in all cases represent the velocities, will be as those Δ^s directly, and the perpendiculars upon the bases inversely, *i. e.* by taking the limiting R^∞ , the velocities of bodies revolving in different orbits are at any points of the orbits universally as the areas described in a given time directly, and the perpendiculars upon the tangents to those points inversely. Hence, if the time be denominated 1, $V = AB$,

but $AB = \frac{2 SAB}{\text{perp.}}$, $\therefore V = \frac{2a}{p}$ where a = area described in a given time, and p = perpendicular.

Prop. 1.—Cor. 2.

65. Suppose first the body to describe uniformly the chords themselves AB , BC ; join AV , then since CV is = and parallel to Bc , it is also = and parallel to AB ; $\therefore BV$, which passes through

the centre S , is the diagonal of the parallelogram $ABCV$; now since the position of BV will not be altered by the magnitudes of AB , and BC , let them be diminished in infinitum, then will they ultimately coincide with the chords of two arcs successively described in equal times (when those arcs are diminished in infinitum), and BV , which always passes through the centre, will ultimately coincide with the diagonal of the parallelogram formed by those chords.

Prop. 1.—Cor. 3.

66. If the body actually moved over AB , BC ; DE , EF , &c. and the force acted impulsively, the force at B would be to the force at E accurately as BV to EZ , they being the uniform effects of the force at those points; but if the force act incessantly, and consequently AB , BC ; DE , EF be diminished in infinitum, the force at B will be to the force at E in the ultimate R° . of $BV : EZ$, *i. e.* as in the last Cor. in the ultimate R° . of the diagonals of the parallelograms formed by the chords of arcs successively described in equal times.

Prop. 1.—Cor. 4.

67. Draw the diagonals CA , DF , which will bisect BV , EZ in m and n , then (Cor. 3) F^ce at $B : F^ce$ at E in the ultimate R° . of $BV : EZ$ or in the ultimate R° . of $Bm : En$; but the ultimate magnitudes and positions of Bm , En are those of the sagittæ of two arcs ABC , DEF described in equal times, which converge to the centre S , and bisect the chords AC , DF when these arcs are diminished in infinitum.

Prop. 1.—Cor. 5.

68. The parabolic arc described by a body falling obliquely at the earth's surface may be deduced in the same manner from the polygonal motion, only in

this case the sagittæ will be equal and parallel to each other; these sagittæ may, as in the former case, be proved to be measures of the force, *i. e.* of the force of gravity at the earth's surface; hence the force of a body moving in any curve will be to the force of gravity in the ultimate R°. of the sagittæ of the arcs described in equal times in the two cases. Now the sagitta of the parabolic arc described in a very small time, as one second, is known by experiment in feet; if \therefore we can find the sagitta of the arc of any other curve described in the same small time in feet, we can make a direct comparison between the centripetal force in the curve and that of gravity.

PROPOSITION II.

69. Let us first suppose that the body describes the polygon A B C D F formed by the chords of this curve, and that it is deflected only at the \angle^s B, C, D, &c.; then since Bc = A B, the body, if not acted upon by any force, would at the end of the second portion of time be found in c, having described Bc; but it is really found in C at that time, having described BC; c C \therefore which completes the \triangle B C c must represent the quantity and direction of the force acting at B, since it is the motion which, when combined with Bc, produces BC the real motion; *i. e.* the force at B must act in a direction parallel to c C; but since S B C (= S A B) = S B c, C c and S B are parallel, \therefore force at B acts in direction B S; and it may be shewn in like manner, that the force at C, D, E, &c. is directed to the same point S. Now let the sides of this polygon be diminished and their N°. increased ad infinitum, in which case the force acts incessantly, and the body describes a curve line; the

demonstration still remains the same, since it did not at all depend upon the magnitudes of AB , BC , &c.

Prop. 2.—Cor. 1.

70. Let SAB , SBC (*Fig. 45*) be two equal Δ^s as in the Prop.; draw cD parallel to BS , then if SBC be greater than SAB , *i. e.* if the description of the areas be accelerated, the vertex of SBC must fall without cD , \therefore if cC be joined, and BF be drawn parallel to it, the centre of force S will be in BF , and \therefore must have moved up from S into that line, or it has declined towards that quarter towards which the body is going; and in the very same manner when the description of the areas is retarded, the vertex of the Δ will fall within cD , or the force will decline to the other side of S , *i. e.* in antecedentia.

Observations on the two last Propositions.

On Polygonal and Curvilinear Motions.

71. Let $ABCD$ (*Fig. 46*) be a polygon described by a body round S , and suppose the straight lines AB , BC , CD , &c. to be described in the same indefinitely small time T . Now of this motion of a body in a polygon, it may be observed, (1) That the force acts only by impulses, which succeed each other after equal intervals, *viz.* when the body is at the points B , C , D , &c., and consequently that the uniform motion of the body in any side of the polygon, as BC , is compounded of two uniform motions; one which would carry it in the original direction which it had at B , *viz.* through BE ($= AB$) in the given time T ; and the other, which would uniformly carry it through EC , parallel to BS , in the same time T .

(2) That this uniform velocity towards the centre is generated the moment the body arrives at B, by the instantaneous impulse of the force, and is just equal to that which a body would acquire by falling from rest in the given time T, by the uniform action of the same force.

Now let us, in the next place, suppose the body to describe the *curve* A B C D, and to be found in the points A, B, C, D, &c. in the same instants of time that the body in the polygon was. Then the body, when at B, will no longer have the direction B E as in the polygon, but the direction B G, which is a tangent to the curve at B; since then, if the force had not acted, the body would have been found in B G, but is really found in C; it is evident that G C must be the space through which the force has drawn the body in the given time T; which line G C, since the force in the indefinitely small time T will not change its direction, must coincide in position with E C. Now it will be shewn, Art. 78, that C A ultimately = 2 C L, and that B G is parallel to C L; \therefore C A ultimately = 2 B G, and \therefore E C ultimately = 2 G C; that is, the deflection in the polygonal motion is ultimately just double the contemporaneous deflection in the curvilinear.

This difference in the deflection is what constitutes the chief distinction betwixt a polygonal and curvilinear motion; and a very little consideration will shew that it is just what ought to take place, from the difference of the hypotheses in the two cases. For since curvilinear motion is a case of *continued* deflection, the velocity towards the centre, in any one indefinitely small portion of time, is a *variable* velocity *beginning from nothing*; whereas in the polygonal motion it is the velocity so acquired continued *uniform* for the same time; consequently, since the force for the indefinitely small time T will be constant, the space described in the former case ought to be only half what is described in the latter. Hence it is per-

fectly legitimate to reason from a polygonal to a curvilinear motion, and the only difference between them is this: that as in the curvilinear motion the force acts incessantly, so, to make up for this, there is a proper corresponding diminution in the space through which it has to draw the revolving body.

Cor. 1. Hence the force is measured, both in the polygonal and curvilinear motion, by the same quantity, viz. by the ultimate value of EC or $2GC$; for in the former case EC being the space uniformly described by the action of the force in the given time in which BE is described, is a proper measure of the intensity of that force; and, in the latter case, since GC is a space freely described from rest in the same given time, $2GC$ will be a measure of the fluxion of the velocity uniformly generated in that time, or a measure of the force.

Cor. 2. Let $SB = y$, then GC being the deflection of the curve from the tangent ultimately $= \frac{1}{2} d^2y$, \therefore force in curve $(\propto 2GC) \propto d^2y$.

Cor. 3. Though the force in the curve is properly measured by *twice* the subtense of the arc described in an indefinitely small given time; yet when the forces to be compared together, are all computed in the same way, it matters not whether we take the subtenses, (as Newton generally does, see Prop. 1, Cor. 4) or their doubles, as the measures of them; the R^o . being the same in both cases. Nevertheless, when the forces so found are to be compared with others derived from a fluxional calculus, (which has always a reference to the polygon) it is absolutely necessary to take the double subtense for the measure of the force.

PROPOSITION IV.

72. Since the bodies (*Fig. 47*) move equally in the

\odot^s , equal areas will in each case be described in equal times; consequently equal sectors or areas will be described round the centres S, s in equal times; \therefore the centripetal forces tend to the centres of the \odot^s . Again let BAE, bae , be two arcs described in the same indefinitely small time, then AC, ac , which bisect the chords and tend to the centres of the \odot^s will be the sagittæ of these indefinitely small arcs; $\therefore F^{\infty}$ at $A : F^{\infty}$ at a in the ultimate R° of $AC : ac$, or of $\frac{\text{chord } AB^2}{AG} : \frac{\text{ch. } a\delta^2}{ag}$ or of $\frac{\text{arc } AB^2}{AG} : \frac{\text{arc } a\delta^2}{ag}$

(Lem. 7). Now let AF, af , be any two arcs described in equal times; then, since the motions are uniform, $AB : ab :: AF : af$, $\therefore F$ at $A : F$ at $a :: \frac{\text{arc } AB^2}{AG} : \frac{\text{arc } a\delta^2}{ag} :: \frac{\text{arc } AF^2}{AS} : \frac{\text{arc } af^2}{as}$

73. If the absolute forces be different, the expression for the force is the same; for the accelerating force is in all cases proportional to the subtense of the arc described in an indefinitely small given time.

Prop. 4.—Cor. 2.

74. Let F and f be the centripetal forces of bodies describing different \odot^s , V and v their velocities, P and p their periodic times; C and c the circumferences of the \odot^s , R and r their radii; then since in all cases of uniform motion, velocity \propto space directly and time inversely, $V : v :: \frac{C}{P} : \frac{c}{p} ::$ (since

the circumferences of \odot^s are as their radii) $\frac{R}{P} : \frac{r}{p}$,

$\therefore V^2 : v^2 :: \frac{R^2}{P^2} : \frac{r^2}{p^2}$; hence $F : f :: \frac{V^2}{R} : \frac{v^2}{r} ::$

$$\frac{R}{P^2} : \frac{r}{p^2}.$$

Note to Prop. 4.—Cor. 7.

75. Let ϕ = absolute force, and the law of the force be $\frac{1}{R^{2n-1}}$; then if bodies revolve round *different*

centres, accelerating force will (Art. 61) $\propto \frac{1}{R^{2n-1}}$,

$$\therefore P \propto \frac{R^n}{\phi^{\frac{1}{2}}} \text{ and } V \propto \frac{\phi^{\frac{1}{2}}}{R^{n-1}}.$$

Introductory Articles to Prop. 4.—Cor. 8.

76. Let P Q E be any curve (*Figs. 48 and 49*), and S any point within it; take any point s , and from it draw any line sp ; suppose the radius vector S P of the curve P Q E to revolve round S, and at the same time let the line sp begin to revolve round s , with an angular velocity always equal to that of S P, and so that sp may always be to S P in a given R° ; then will the curve, traced out by p , be similar to the curve P Q E (Art. 27). The points S, s , are called points similarly situated; and if $\angle^s p s q, p s c, \&c. = \angle^s P S Q, P S C, \&c.$ respectively, then $p, q, c, \&c.$, and P, Q, C, $\&c.$, are called similar points; $sp, sq, sc, \&c.$, and $SP, SQ, SC, \&c.$ similar or homologous lines; $pq, pc, qc, \&c.$, and P Q, P C, Q C, $\&c.$ similar or homologous arcs; and $psq, psc, qsc, \&c.$, and P S Q, P S C, Q S C, $\&c.$ similar areas of the similar figures respectively.

77. From the definition of similar figures, it follows, (1) That if S, s be points similarly situated, the chords of similar arcs P Q, $p q$, make equal \angle^s with the radius vectors S P, sp ; and are to each other in a given R° . For since $PS : SQ :: ps : sq$, and $\angle PSQ = \angle psq$, $\therefore \triangle PSQ, psq$ are similar; $\therefore \angle QPS = \angle qps$, and $PQ : pq :: PS : ps$ in a given R° . (2) That the tangents to similar

points P, p , make equal \angle^s with the radius vectors to those points; for $\angle SPQ$ always $= \angle spq$ by the first case, \therefore they are ultimately equal; but these \angle^s are ultimately the \angle^s between the tangents and the radii, $\therefore \angle SPR = \angle spr$. (3) That similar arcs PE, pe , as also similar areas PSE, pse , of similar figures are to each other in a given R° ; for let the similar arcs PE, pe , be divided into the same number of similar arcs $PQ, QC; pq, qc$, &c., and draw the chords; then, by the first case, these chords are to one another in a given R° , viz. in the R° of $SP : sp$; consequently the sums of the chords are in the same given R° ; and since this is always the case, they are also ultimately in this given R° . Hence, Cor. Lem. IV., the arc PE : the similar arc pe in that given R° ; i. e. similar curves, or similar arcs of similar curves, are to one another as any similar or homologous radius vectors. And in the same manner, by dividing the similar areas into similar parts, we have the areas of similar curves, or of similar parts of similar curves to one another in a given R° , viz. in the duplicate R° of any homologous radius vectors. (4) That the similarly situated chords of curvature PV, pv to similar points of similar figures, are as the radius vectors to those points, or as any other homologous lines in the figures. For draw the subtenses QR, qr of the evanescent arcs PQ, pq parallel to SP, sp ; then, by the nature of the \odot of curvature, $PV : PQ :: PQ : QR$; and $pv : pq :: pq : qr$; but by similar \triangle^s $PQ : QR :: pq : qr$, $\therefore PV : pv :: PQ : pq :: SP : sp$, or as any homologous lines in the figures.

78. Let APQ be any arc, (*Fig. 48*) AQ the chord of that arc; S the centre of force. Draw the radius SP bisecting the chord AQ , then will PN be the sagitta of the arc APQ at the point P where SN meets the curve; draw the tangent BR , and the subtenses QR and AB parallel to SP , and let PV be the chord of curvature at the point P ; this being

premised, it follows (1) That this sagitta will ultimately bisect the arc APQ , or that the point P is ultimately in the middle of the arc APQ : for since $QN = NA$, and that QN ultimately $=$ arc QP , and AN ultimately $=$ arc AP , \therefore arc QP ultimately $=$ arc AP . (2) That the chord ANQ is ultimately parallel to the tangent BR drawn to the curve at the point P ; for AB is ultimately to QR as PB^2 or PA^2 to PR^2 or PQ^2 , *i. e.* in a R° of equality; they are also parallel, $\therefore AQ$ and BR are also ultimately parallel. (3) That the evanescent subtense QR or AB is ultimately $=$ to the sagitta PN , which ultimately bisects the arc APQ ; for RN is ultimately a parallelogram, $\therefore QR$ and PN are ultimately equal.

Prop. 4.—Cor. 8.

79. Let $AP E$, $ap e$ (*Figs. 48 and 49*) be two similar figures, having the centres of force S, s similarly situated in them, P and p similar points of the orbit, APQ , apq two arcs described in the same time, whose middle points are ultimately P and p , join SP , sp ; then since PN , pn ultimately bisect the arcs APQ , apq , they are ultimately the sagittæ of those arcs (Art. 78), \therefore centripetal force in P : centripetal force in p in the ultimate R° of $PN : pn$; or of

$$QR : qr \text{ (Art. 78), or of } \frac{\overline{QPA}^2}{PV} : \frac{\overline{qp a}^2}{pv}, \text{ or by}$$

reason of similar figures, (Art. 77) in the ultimate R° .

$$\text{of } \frac{\overline{QPA}^2}{PS} : \frac{\overline{qp a}^2}{ps}.$$

Hence the centripetal forces in these similar points are also as the squares of the velocities directly, and the distances inversely; for the velocities are in the ultimate R° of the arcs APQ , apq described in the same time.

Again, the centripetal forces at those similar points

are also as the distances directly, and the squares of the periodic times inversely. For let APQ , apq no longer represent evanescent arcs described in the same time, but *similar* evanescent particles of the similar curves, described in the indefinitely small times T and t ; also let V and v represent the velocities at P and p ; A and a the whole areas of the similar figures; P and p the periodic times; then since APQ , apq may be considered as described uniformly, $V : v :: \frac{APQ}{T} : \frac{apq}{t} :: \frac{SP}{T} : \frac{sp}{t}$

(by Art. 77); but F at $P : F$ at $p :: \frac{V^2}{SP} : \frac{v^2}{sp}$,

$\therefore F$ at $P : F$ at $p :: \frac{SP}{T^2} : \frac{sp}{t^2}$. But since $T : P :: SQA : A$ and $t : p :: sqa : a$ and that $SQA : sqa :: A : a$ (Art. 77), $\therefore T : t :: P : p$; hence F at $P : F$ at $p :: \frac{SP}{T^2} : \frac{sp}{t^2} :: \frac{SP}{P^2} : \frac{sp}{p^2}$.

Hence since $F \propto \frac{V^2}{D}$ and as $\frac{D}{P^2}$ in similar figures, the preceding Cors. will apply to bodies describing similar parts of similar curves, having their centres of force similarly situated; for Ex. if the periodic time be as the n^{th} power of any homologous radius vectors, the forces will be reciprocally as the $2n-1^{\text{th}}$ power of any homologous radius vectors, and the contrary; and note, when distances are mentioned, the similar or homologous distances are always understood.

Prop. 4.—Cor. 9.

80. Let PA (Fig. 50) be an arc described in any time, PB the space fallen through in the same time by the force at P continued uniform; take PQ an evanescent arc, QR the subtense parallel to PS , and

complete the parallelogram; then the evanescent subtense $Q R$ or $P C$ is the space fallen through by the centripetal force, in the same time that the arc $P Q$ is described (Art. 71). Let T and t represent the times of falling through $P B$ and $P C$, or of describing the arcs $P A$, $P Q$; then since S varies as T^2 , when F is given, $P C : P B :: t^2 : T^2 :: P Q^2 : P A^2$

$$:: \frac{P Q^2}{P G} : \frac{P A^2}{P G}; \text{ but } P C = \frac{P Q^2}{P G}, \therefore P B = \frac{P A^2}{P G}$$
 and $P B : P A :: P A : P G$.

Deductions from Prop. 4 and its Cors.

81. *Suppose a body to revolve uniformly in a circle; required the space through which it must fall, when acted upon by the centripetal force at the circumference continued uniformly, in order to acquire the velocity it has in the circle.*

Let $P B$ (Fig. 50) = required space, and suppose $P A$ to be the arc uniformly described in the time of the body's falling through $P B$, then $P A = 2 P B$; but (Cor. 9) $P B : P A :: P A : P G$; i. e. $P B : 2 P B :: 2 P B : P G$ or $2 P S$, $\therefore P B = \frac{P S}{2} = \frac{1}{2}$ radius.

82. *Required the same in any curve.*

Let $P O$ (Fig. 48) = required space, $P V$ = chord of curvature, $P Q$ an indefinitely small arc, and $Q R$ (= $P N$) the subtense of the \angle of contact; then since the velocities are as the spaces uniformly described in the same time, velocity in curve : velocity acquired through $P N :: P Q : 2 P N$, \therefore

V^2 in curve : V^2 through $PN :: PQ^2 : 4 PN^2$; but
 V^2 thro' $PN : V^2$ thro' PO , or V^2 in curve :: $PN : PO$
 $\therefore PQ^2 \times PN = 4 PN^2 \times PO$, and $PO = \frac{PQ^2}{4PN}$
 $\frac{PQ^2}{4PN} = \frac{PV}{4} = \frac{1}{4}$ of chord of curvature.

Or thus, by Art. 96, $S = \frac{V^2}{2F}^*$, but $V^2 = F \times \frac{1}{2}PV$, $\therefore S = \frac{F \cdot \frac{1}{2}PV}{2F} = \frac{PV}{4}$.

83. *Required the velocity and periodic time of a body revolving in a circle at the earth's surface.*

Let V = velocity required, measured by the arc described in one second, r = radius of the earth, $g = 32\frac{1}{2}$ feet; then in general $V^2 = 2FS$ = in this case $2gS = (\text{Art. 81}) 2g \times \frac{r}{2} = gr$, $\therefore V = \sqrt{gr}$ = feet per second.

Again, to find the periodic time, put $\pi = 3.14159$ &c.

\therefore whole circumference = $2\pi r$ \therefore P. T. = $\frac{2\pi r}{v} = \frac{2\pi r}{\sqrt{gr}} = \pi \sqrt{\frac{4r}{g}}$ in seconds, r being expressed in feet.

* The following are the formulæ applicable to the rectilinear motion of bodies acted upon by constant or variable forces; deduced upon the supposition that gravity is represented by $g = 32\frac{1}{2}$ feet, its effect produced in 1".

Force constant.

$$v = Ft$$

$$s = \frac{vt}{2}$$

$$s = \frac{Ft^2}{2}$$

$$s = \frac{v^2}{2F}$$

Force variable.

$$ds = Fdt$$

$$ds = vdt$$

$$v dv = Fds$$

$$F = \frac{d^2s}{dt^2}$$

Cor. 1. The velocity in miles $\approx 4,92088$ per second, and the P. T $\approx 1^{\text{hr}}, 24^{\text{m}}, 27^{\text{s}}$.

Cor. 2. Hence if a body be projected from any point P on the earth's surface in a horizontal direction with the velocity of $\sqrt{g r}$ feet in a second, it will revolve as a secondary round the earth; for suppose a body so to revolve, then at the point P it will have the same direction, the same velocity, and be acted upon by the same force as the projected body, \therefore if the revolving body continue to move round the earth in a \odot , the projected body must also revolve in the same manner.

Cor. 3. Hence also having given the radius of the circle described by any revolving body, and its velocity or periodic time, we can compare the centripetal force with that of gravity. For since by Prop. 4, F.

$\propto \frac{V^2}{R}$, $F : f :: \frac{V^2}{R} : \frac{v^2}{r}$; call f the force of gravity, then will $r =$ the earth's radius, and $v^2 = g r$, $\therefore F : \text{gravity} :: \frac{V^2}{R} : g$.

Again, since $F : f :: \frac{R}{P^2} : \frac{r}{p^2}$; call f the force of gravity, then will $r =$ the earth's radius and $p^2 = \frac{4 \pi^2 r}{g}$, $\therefore F : \text{gravity} :: \frac{R}{P^2} : \frac{g r}{4 \pi^2 r} :: \frac{R}{P^2} : \frac{g}{4 \pi^2}$; where R must be expressed in feet, and P in seconds.

Cor. 4. To find an Equation for the force we have by last Cor. $F : \text{force of gravity} :: \frac{V^2}{R} : g$; now let the force of gravity be represented by its effect produced in a given time as $1''$, or by g ; then $F : g :: \frac{V^2}{R} : g$, $\therefore F = \frac{V^2}{R}$. And upon the same suppo-

sition it will be found that $F \propto \frac{4 \pi^2 R}{P^2}$.

To shew the use of the two last Cors. let us apply them to the solution of the following Problems.

84. 1. *Let a body revolve in the circle M E D (Fig. 51) with a velocity acquired in falling through M B by gravity; required the Ratio of the centripetal force to that of gravity.*

Let V = velocity in curve, then $V^2 \propto 2g \times MB$; hence since F varies as $\frac{V^2}{R}$, we have as in

first part of Corollary 3, $F : \text{gravity} :: \frac{2g \times MB}{MS} : g :: 2MB : MS$.

Cor. If the body be made to revolve uniformly in the \odot M E D by means of a weight fixed to a string; then we shall have the tension of the string arising from the centrifugal force of the body, to the tension arising from the same weight hanging freely, in the above R^o. of $2MB : MS$.

2. *Compare the force of gravity with the centrifugal force at the equator.*

Let P = time of the earth's revolving round its axis in seconds, R = radius of the earth in feet; then since F varies as $\frac{R}{P^2}$, we have as in 2d part of Cor. 3, Centrifugal force at Equator : Force of gravity :: $\frac{R}{P^2} : \frac{g}{4\pi^2}$.

3. *Given the moon's periodic time, and the radius of her orbit; to find how far she would fall in 1" supposing her projectile motion to be destroyed.*

Let P = moon's periodic time, R = radius of her

orbit, then since F varies as $\frac{R}{P^2}$ we have by Cor. 4

$$F = \frac{4\pi^2 R}{P^2}, \therefore S = \frac{FT^2}{2} = \frac{2\pi^2 R}{P^2}.$$

4. *Required the periodic time of a body describing a conical surface.*

The body at B (*Fig. 52*) is retained in its orbit by three forces; gravity in direction SA , tension of the string in direction BS , and centrifugal force in direction AB , \therefore the sides of the $\triangle SAB$ will represent them; hence centrifugal force or F : gravity or g

$:: AB : SA :: F = \frac{g \cdot AB}{SA}$; hence since F varies as

$\frac{R}{P^2}$, we have $\frac{g \cdot AB}{SA} : g :: \frac{AB}{P^2} : \frac{g}{4\pi^2} \therefore P^2 =$

$$\frac{4\pi^2 SA}{g} \text{ and } P = \pi \sqrt{\frac{4SA}{g}}.$$

Cor. 1. Hence periodic time : T through $2SA ::$

$$\pi \sqrt{\frac{4SA}{g}} : \sqrt{\frac{4SA}{g}} :: \pi : 1 :: \text{circumference of}$$

\odot : diameter.

Cor. 2. Required the periodic time when the tension of the string = 3 times the weight of the body.

Let $SB = L$; then will SA , by Problem, = $\frac{L}{3}$,

$$\therefore F = \frac{g \cdot AB}{SA} = \frac{g \cdot 3AB}{L} : \text{hence } \frac{g \cdot 3AB}{L} : g :: \frac{AB}{P^2}$$

$$: \frac{g}{4\pi^2}, \therefore P^2 = \frac{4\pi^2 SA}{g} = \frac{4\pi^2 L}{3g}, \text{ and } P = \pi$$

$$\sqrt{\frac{4L}{3g}}.$$

PROPOSITION VI.

85. Let $B P Q$, $b p q$, (*Fig. 53*) be two indefinitely small arcs described in the times T , t ; S and s the centres of force; $S C P$, $s c p$, the radii vectors, which ultimately bisect the chords $B Q$, $b q$, and \therefore also ultimately bisect the arcs $B P Q$, $b p q$, in P and p , (*Art. 78*); draw the tangents $P R$, $p r$, and the subtenses $Q R$, $q r$ parallel to $S P$, $s p$; let also $K P L$ be an arc described in the same time with $b p q$, and which shall be ultimately bisected by $S P$; then will its chord $K L$ also be ultimately bisected by $S P$, and consequently $P C$, $P N$, $p c$, are ultimately the sagittæ of the arcs $B P Q$, $K P L$, $b p q$. Hence since $K P L$, $b p q$ are arcs described in the same time,

$P N : p c :: F \text{ at } P : F \text{ at } p$; and by *Cor. 2, Lem. II.*
 $P C : P N :: P Q^2 : P L^2 :: B P Q^2 : K P L^2 :: T^2 : t^2$

$\therefore P C : p c :: F \times T^2 : f \times t^2$; and $F : f :: \frac{P C}{T^2}$

$: \frac{p c}{t^2}$; or the force in the middle of the arcs varies as

sagittæ of those arcs

time² in which they are described.

This Prop. is general, being applicable to different bodies revolving in the same or different orbits, and round the same or different centres of force.

Prop. 6.—Cor. 1.

86. Let $P Q$ and $p q$ (*Fig. 54*) be two indefinitely small arcs, $P R$, $p r$ tangents at P and p ; $Q R$, $q r$ subtenses parallel to $S P$, $s p$; then $Q R$, $q r$ are ultimately = the sagittæ of two arcs whose middle points are P , p (*Art. 78*) or the sagittæ of double the arcs $P Q$, $p q$; also the time of describing $2 P Q$ is

ultimately proportional to the time of describing P Q;

$$\text{hence } F \text{ at } P : F \text{ at } p :: \frac{QR}{T^2 \cdot 2 PQ} : \frac{qr}{T^2 \cdot 2 p q} ::$$

$$\frac{QR}{T^2 \cdot PQ} : \frac{qr}{T^2 \cdot p q} :: (\text{since in the same curve}$$

the areas are proportional to the times) $\frac{QR}{SPQ^2} :$

$$\frac{qr}{Spq^2} :: \frac{QR}{\frac{1}{2}SP \cdot QT^2} : \frac{qr}{\frac{1}{2}Sp \cdot q^2} :: \frac{QR}{SP^2 \cdot QT^2} :$$

$\frac{qr}{Sp^2 \cdot q^2}$ i. e. the centripetal force, in different points of the same curve, is in the ultimate Ratio of $SP^2 \cdot QT^2$ inversely.

Notes to Prop. 6.—Cor. 1.

87. $\frac{SP^2 \cdot QT^2}{QR}$ is called a solid, because it is of three dimensions; for $\frac{QT^2}{QR}$ being a third proportional to two lines QR and QT, must also itself be a line, and SP^2 is the product of two lines; $\therefore \frac{SP^2 \cdot QT^2}{QR}$ is the product of three lines, and is therefore analogous to the solid content of a parallelepiped, whose three adjacent sides are the three lines. Again, not only is the Ratio $\frac{SP^2 \cdot QT^2}{QR} : \frac{Sp^2 \cdot q^2}{qr}$ a finite Ratio upon the coincidence of P and Q, but the terms of the R^o. also are always finite; for SP^2 is finite, also since the Δ^s SPY, QNT are ultimately similar SY² : $SP^2 :: QT^2 : QN^2 :: \frac{QT^2}{QR} : \frac{QN^2}{QR}$; but the

limit of $\frac{QN^2}{QR}$ is the chord of curvature PV , a finite line, \therefore also the limit of $\frac{QT^2}{QR}$, and consequently of $\frac{SP^2 \cdot QT^2}{QR}$, is finite.

88. The formula for the centripetal force, given in the above Corollary, is only applicable to the finding the variation of the force, in different points of the *same* orbit, and does not extend to different curves; for in the proof of that Corollary, the area SPQ was assumed proportional to the time in which it was described; which is not generally true for different orbits. We may, however, find a general equation

for the force thus—In all cases $F \propto \frac{\text{Sag}^2}{T^2} \therefore F :$

gravity (g) $:: \frac{QR}{T^2} : \frac{\frac{1}{2}g}{1^2} \therefore F = \frac{2QR}{T^2}$. Now

let a = area in $1''$, then $a : SPQ :: 1'' : T$

$$= \frac{SPQ}{a} = \frac{SP \times QT}{2a} \therefore T^2 = \frac{SP^2 \times QT^2}{4a^2} \therefore$$

$$F = \frac{8a^2 \times QR}{SP^2 \times QT^2}, \text{ which is a general expression ap-}$$

plicable to different orbits round the same or different centres of force. If A = whole area of the curve, and P = periodic time, we have $P : 1'' :: A : a =$

$\frac{A}{P}$; \therefore in this section and the following we may, if

necessary, for $8a^2$, substitute $\frac{8A^2}{P^2}$.

Prop. 6.—Cor. 2.

89. Draw SY, Sy (*Fig. 54*) perpendicular to the tangents at P and p ; then since $SP \times QT = SY \times QP$, being each ultimately double of the ΔSQP , and that $Sp \times qt = Sy \times qp$ for the

same reason, \therefore F. at P : F. at p in the ultimate R^o.

$$\text{of } \frac{QR}{SY^2 \times QP^2} : \frac{qr}{Sy^2 \times qp^2}.$$

Notes to Prop. 6.—Cor. 2.

90. For the reasons given in Art. 87, $\frac{SY^2 \times QP^2}{QR}$ is a solid, and it is also finite upon the coincidence of Q and P; for SY^2 is finite; and $\frac{QP^2}{QR}$ is ultimately = chord of curvature PV, a finite line.

91. The above Corollary is only applicable to different points of the same curve, for the reasons given in Art. 88; but it may be made general by the method pursued in the former Corollary, from which it appears that the centripetal force = $\frac{8a^2 \times QR}{SY^2 \times QP^2}$.

Prop. 6.—Cor. 3.

92. By Cor. 2, F. at P : F. at p :: $\frac{QR}{SY^2 \times QP^2}$: $\frac{qr}{Sy^2 \times qp^2}$ ultimately, but $\frac{QP^2}{QR}$ is ultimately = chord of curvature at P = PV, and $\frac{qp^2}{qr} = pv$, \therefore F. at P : F. at p :: $\frac{1}{SY^2 \times PV} : \frac{1}{Sy^2 \times pv}$.

Notes to Prop. 6.—Cor. 3.

93. In general $F = \frac{8a^2}{SY^2 \times PV}$.

94. From this Cor. may easily be deduced De Moivre's expression for the centripetal force. For let PN (Fig. 55) be the curve, PF the diameter of curvature, and PC = radius of curvature = R, the

rest as before; then by similar \triangle^s , $SP : SY :: PF$
 $(2R) : PV = \frac{2R \times SY}{SP}$, $\therefore F$ varies inversely
 as $\frac{SY^3 \times R}{SP}$; which expression may be made general
 in the same manner as the rest.

Prop. 6.—Cor. 4.

95. By Cor. 3, F . at $P : F$. at $p :: \frac{1}{SY^2 \times PV}$
 $: \frac{1}{Sy^2 \times pv}$, but (Cor. 1, Prop. 1) $SY^2 : Sy^2 ::$
 $V.^2$ at $p : V.^2$ at P ; $\therefore F$. at $P : F$. at $p :: \frac{V.^2$ at $P}{PV}$
 $: \frac{V.^2$ at $p}{pv}$, or the centripetal force $\propto \frac{V.^2}{\text{ch. curv}^e}$.

Note to Prop. 6.—Cor. 4.

96 In general $F = \frac{8a^2}{SY^2 \times PV}$, but, Art. 64,
 $SY^2 = \frac{4a^2}{V.^2}$, $\therefore F = \frac{V.^2}{\frac{1}{2}PV}$. Hence the formula
 $\frac{V.^2}{PV}$ for the centripetal force in Cor. 4 is general,
 and applicable either to one or different orbits, round
 the same or different centres of force, and the reason
 why a general expression should be deduced from
 one that is not general, is obvious from the method
 of proof observed in this Note.

Or the Equation may be thus deduced. In general
 $V.^2 = 2FS = 2F \times \frac{PV}{4}$ (Art. 82) $= F \times$
 $\frac{PV}{2}$, $\therefore F = \frac{V.^2}{\frac{1}{2}PV}$.

*Introductory Articles to the remaining Parts
of this Section.*

97. *If a body, urged by any centripetal force, is moved in any manner; and another body ascends or descends in a right line; and their velocities are equal in any one case of equal altitudes, their velocities will be equal at all equal altitudes.*—NEWT. LIB. I., PROP. 40.

Let any body descend from A (*Fig. 56*) through D, E, to the centre C; and let another body be moved from V in the curve line V I K *k*. With the centre C, at any intervals, let the concentric circles D I, E K be described, meeting the right line A C in D and E; and the curve line V I K in I and K. Let I C be joined meeting K E in N; and let the perpendicular N T be drawn to I K; and let the interval D E or I N of the circumferences of the circles be very small; and let the bodies have equal velocities in D and I. Since the distances C D, C I are equal, the centripetal forces in D and I will be equal. Let these forces be expressed by the same equal lines D E, I N; and if one force I N is resolved into two N T and I T; the force N T, by acting in the direction of the line N T perpendicular to I T K the path of the body, will not change the velocity of the body in that path, but will only draw the body from its rectilinear course, and make it turn aside continually from the tangent of the orbit, and proceed in the curvilinear path I T K *k*. In producing this effect, that whole force will be employed: but the other force I T, by acting in the direction of the course of the body, will be wholly employed in accelerating it, and in a very small given time will produce an acceleration propor-

tional to itself. Therefore the accelerations of the bodies in D and I, produced in equal times (if the limits of the ratios of the nascent lines D E, I N, I K, I T, N T are taken) are as the lines D E, I T; but in unequal times, are as those lines and the times jointly. But the times in which D E and I K are described, because of the equal velocities, are as the spaces described D E and I K; and therefore the accelerations, in the course of the bodies through the lines D E and I K, are as D E and I T, D E and I K jointly; that is, as $D E^2$ and the rectangle $I T \times I K$. But the rectangle $I T \times I K$ is equal to $I N^2$, that is equal to $D E^2$; and therefore equal accelerations are generated in the transit of the bodies from D and I to E and K: therefore the velocities of the bodies in E and K are equal: and by the same argument they will always be found equal in all subsequent equal distances. Which was to be demonstrated.

By the same argument, bodies with equal velocities, and equally distant from the centre, will be equally retarded in their ascent to equal distances. Which was to be demonstrated.

Hence the following Corollary.

Cor. Let C be the centre of force, A the point from which a body must fall by the action of the force to acquire the velocity in the curve at V, C D and C I equal distances from the centre C in the straight line and curve; v = velocity at I, $C I = x$, F = force in direction I C, then will $v dv = - F dx$; for v , dv , F and dx are the same, both in the curve and straight line. Hence, according to whatever law the velocity of the body descending in the right line V C may vary, in the same manner will the velocity in the curve also vary.

98. *To find the fluxional expression for the law of the force, supposing a body to revolve round a fixed centre.*

Let y = distance of the body from the centre of

force, p = perpendicular upon the tangent, F = force, and v = velocity at the distance y ; then $v^2 = \frac{4a^2}{p^2} \therefore v dv = -\frac{4a^2 dp}{p^3}$; but, Cor. Art. 97, $v dv = -F dy$, $\therefore F = \frac{4a^2 dp}{p^3 dy} \propto \frac{dp}{p^3 dy}$.

Or the same immediately follows from Prop. 6,

$$\begin{aligned} \text{Cor. 3, for } F &= \frac{8a^2}{SY^2 \times PV} = \frac{8a^2}{p^2 \times \frac{2p dy}{dp}}, \\ &= \frac{4a^2 dp}{p^3 dy}. \end{aligned}$$

Ex. 1. *Required the law of the force in the hyperbolic spiral.*—Here $p = \frac{ay}{\sqrt{a^2 + y^2}} \therefore \frac{1}{p^2} = \frac{1}{y^2} + \frac{1}{a^2}$
 $\therefore \frac{dp}{p^3} \propto \frac{dy}{y^3}$ and $F \propto \frac{dp}{p^3 dy} \propto \frac{1}{y^3}$.

Ex. 2. *Required the same in the spiral of Archimedes.*—Here $p = \frac{y^2}{\sqrt{b^2 + y^2}} \therefore \frac{1}{p^2} = \frac{b^2}{y^4} + \frac{1}{y^2} \therefore$
 $\frac{2 dp}{p^3} = \frac{4b^2 dy}{y^5} + \frac{2 dy}{y^3}, \therefore F \propto \frac{dp}{p^3 dy} \propto \frac{2b^2}{y^5} + \frac{1}{y^3}$.

Ex. 3. *Required the same in the involute of a circle.*—Let r = radius of the \odot , then by the nature of the curve $p^2 = y^2 - r^2$, $\therefore \frac{1}{p^2} = \frac{1}{y^2 - r^2}$, and
 $\frac{dp}{p^3 dy} \propto \frac{y}{y^2 - r^2} \propto \frac{y}{p^4}$.

Ex. 4. *Required the same when the square of the ve-*

locity is proportional to the logarithm of the distance

Here $v^2 \propto \log. y$, $\therefore \frac{1}{p^2} \propto \log. y$, $\therefore \frac{dp}{p^3 dy} \propto -\frac{1}{y}$,
the force \therefore is repulsive, and varies inversely as the distance.

99. *The squares of the velocity of bodies revolving in any curve, are in the joint Ratio of the accelerating forces, and chords of curvature.*

For (Art. 96) $V^2 = F \times \frac{1}{2} P V \propto F \times P V$.

100. *To compare the velocity in any point of the curve, with the velocity of a body revolving in a circle at the same distance.*

$V^2 \propto F \times P V$, and in this case F is the same in the curve and \odot , $\therefore V^2 : v^2 :: P V : p v$.

Cor. Let y = distance from the centre of force, p = perpendicular on the tangent, then if for $P V$, $p v$, we substitute their values, we shall have $V^2 : v^2$
 $:: \frac{2 p dy}{dp} : 2 y :: \frac{dy}{y} : \frac{dp}{p}$.

101. *If a body revolve in a curve of any kind round a centre of force, to compare the \angle^r velocity of the perpendicular upon the tangent, with that of the radius vector.*

Let P, Q (*Fig. 8*) be two points in the curve indefinitely near to each other, to which the tangents $P Y, Q y$ are drawn; let fall the perpendiculars $S Y, S y$ upon the tangents $P Y, Q y$, and from P and Q draw $P C, Q C$ perpendicular to the curve at P and Q , which will meet in C , the centre of curvature; then since $P C, Q C$ are respectively parallel to $Y S, y S$, the $\angle P C Q = \angle Y S y$; hence \angle^r velocity of perpendicular : \angle^r velocity of distance $:: \angle Y S y :$
 $\angle P S Q :: \angle P C Q : \angle P S Q :: \frac{Q P}{P C} : \frac{Q T}{S P} ::$

$$\frac{CP}{CP} : \frac{PO}{SP} :: SP : PO :: 2SP : PV :: 2y : \frac{2p dy}{dp} :: \frac{dp}{p} : \frac{dy}{y}.$$

Cor. Hence, and by Art. 100, V^2 in curve : V^2 in \odot at the same distance :: \angle^r velocity of distance : \angle^r velocity of perpendicular; and \therefore the velocity in the curve = velocity in the \odot at the same distance, when the \angle^r velocity of the distance = the \angle^r velocity of the perpendicular.

102. *The angular velocity in any curve is as the area described in a given time directly, and the square of the distance inversely.*

Let PSQ, psq (Fig. 57), be two indefinitely small \angle^s ; A and a the areas described about S and s in the same given time, then \angle^r velocity about S :

$$\angle^r \text{ velocity about } s :: \angle PSQ : \angle psq :: \frac{QT}{SP} : \frac{qt}{sp} :: \frac{SP \cdot QT}{SP^2} : \frac{sp \times qt}{sp^2} :: \frac{A}{SP^2} : \frac{a}{sp^2}.$$

Cor. In the same curve $A = a$, $\therefore \angle^r$ velocity $\propto \frac{1}{\text{dist.}^2}$

103. *To find the variation of the paraentric velocity in any curve.*

Let PQ (Fig. 58) represent the velocity in the curve; draw QT perpendicular to SP , then will PT represent the velocity towards the centre; to find which, put $SP = y$, $SY = p$, then $SP : PY ::$

$$PQ : PT = \frac{PQ \times PY}{SP} = \frac{\frac{2a}{p} \times \sqrt{y^2 - p^2}}{y} \propto \frac{\sqrt{y^2 - p^2}}{p y}$$

104. Required the rate at which the linear velocity decreases in any curve.

Let $SP = y$, $SY = p$, $v =$ velocity in curve at P , then since $v \propto \frac{1}{p}$, $-dv \propto -\frac{dp}{p^2}$ or $dv \propto \frac{dp}{p^2}$; from the equation to the curve get a value of p in terms of y , and consequently a value of $\frac{dp}{p^2}$ in terms of y and dy ; but $\sqrt{y^2 - p^2} : p :: PT$ or $dy : QT$
 $= \frac{p \, dy}{\sqrt{y^2 - p^2}}$, $\therefore \frac{p \, y \, dy}{\sqrt{y^2 - p^2}} = SP \times QT = \text{area}$
described in a given time $= 1$, $\therefore dy = \frac{\sqrt{y^2 - p^2}}{p \, y}$;
substitute this value of dy in the proportional equation $dv \propto \frac{dp}{p^2}$, and the thing required is done.

105. Required the rate at which the \angle^r velocity decreases in any curve.

Let α represent the \angle^r velocity, then $\alpha \propto \frac{1}{y^2}$, \therefore
 $-d\alpha \propto -\frac{dy}{y^3}$ or $d\alpha \propto \frac{dy}{y^3}$; but by the last Article,
 $dy = \frac{\sqrt{y^2 - p^2}}{p \, y} \therefore d\alpha \propto \frac{\sqrt{y^2 - p^2}}{p \, y^4}$.

Of the nature, variation, &c., of the centrifugal force.

106. Supposing a body to revolve about a centre of force, and the motion in the curve to be resolved into two, one in the direction of the radius vector,

and the other perpendicular to it, it is evident that that part of its motion, which is perpendicular to the radius vector, will give the body a tendency to recede from the centre. This tendency of the body to recede from the centre, in consequence of its rotation round it, is called the *centrifugal* force, and the space by which it thus recedes, in an indefinitely small given time, is the measure of this force.

Thus let PQ (*Fig. 57*) be an arc described in an indefinitely small given time, S the centre of force; resolve PQ into PT and TQ , and with S as centre and SQ as radius describe the circular arc Qx . Now since PQ represents the whole motion of the body, PT will represent that part of it which is towards the centre; and by this *alone* the body would be found at the distance ST from the centre at the end of the given time; but in consequence of the motion TQ perpendicular to SP , it is really found at Q at the end of the given time, and at a distance from the centre $= SQ$ or Sx . In consequence \therefore of the perpendicular motion TQ , the body has receded from the centre through a space $= Tx$, which \therefore by the definition is a measure of the centrifugal force.

107. Strictly speaking, the term *force*, applied to this tendency of a body to recede from the centre in consequence of its rotation round it, is inaccurate; it being merely the effect of that property in all matter of persevering in its rectilineal direction: it is \therefore denominated a force, merely because we must employ a centripetal force to balance it, just as we suppose a *resisting* vis inertiae because we must employ force to move a body.

108. From the above definition of a centrifugal force, it follows (1), That if a body revolve in a circle, the centripetal and centrifugal forces are equal; for TP (*Fig. 59*) is the space through which the body recedes from the centre in consequence of the perpendicular motion TQ , and \therefore represents the centrifugal force; also PT taken in a contrary direction represents the effect of the centripetal force, \therefore &c.

Or the same conclusion may be deduced from considering that the body always continues at the same distance from the centre, and \therefore through whatever space it must recede from the centre in consequence of the centrifugal force, through the same space must it approach the centre in consequence of the centripetal.

(2) That if a body revolving in any curve come to an apse, it will, after that, approach to, or recede from, the centre, according as the centripetal is greater, or less, than the centrifugal force. For let PQ (Fig. 60) be the curve, P the apse, PA a \odot described with S as centre and SP as radius, and which falls without the curve PQ ; then by constructing the figure as before, we shall have Tx to represent the centrifugal force, and PT the centripetal; but since SA is greater than SQ , PT is greater than Tx , *i. e.* when the body approaches the centre from an apse, centripetal force is greater than centrifugal, \therefore conversely, &c. But if $\odot PA$ (Fig. 61) falls within the curve, *i. e.* if the body recedes from the centre, Tx is greater than PT , *i. e.* centrifugal force is greater than centripetal, \therefore &c. Or the same conclusion may be deduced from considering that since the whole motion towards the centre is the effect of the centripetal force, and the whole motion from it the effect of the centrifugal, the body must approach to, or recede from, the centre, according as the first is greater or less than the second.

(3) That if the body be not at an apse, *i. e.* if the direction of the body's motion be oblique to the radius vector, the body's approach to, or recess from, the centre, does not depend upon the centripetal force being greater or less than the centrifugal; for in this case PT (Fig. 62) $= Py + yT = Py + QR$, *i. e.* the motion directly towards the centre is made up of the motion QR in that direction arising from the action of the centripetal force, together with that part of the tangential motion represented by Py ,

which is in the direction P S; hence, in consequence of this tangential motion, the body may approach to the centre S, even though the centrifugal force be greater than the centripetal, as is represented in the figure, and the contrary.

(4) That in all cases the centrifugal is equal and opposite to the centripetal force of a body revolving in a circle at the same distance, and with the same \angle^r velocity; for if x Q represent a circular arc described in the same given time in which the arc P Q is described, x T will be a measure of the centripetal force in that circle, but T x has been shewn also to represent the centrifugal force of the body revolving in the curve P Q.

109. *The centrifugal force in different points of different curves is proportional to the square of the area described in a given time directly, and the cube of the distance inversely.*

For centrifugal force at P (Fig. 57) : D° . at p ::

$$T x : t x :: \frac{Q T^2}{S P} : \frac{q t^2}{s p} :: \frac{S P^2 \times Q T^2}{S P^3} : \frac{s p^2 \times q t^2}{s p^3}$$

$$:: \frac{A^2}{\text{Dist.}^3} : \frac{a^2}{\text{Dist.}^3}, \text{ or (Art. 64) } :: \frac{V^2 P^2}{D^3} : \frac{v^2 p^2}{d^3}.$$

Cor. 1. In the same curve $A \propto a$, i. e. in different points of the same curve, the centrifugal force $\propto \frac{1}{\text{Dist.}^3}$.

Cor. 2. To find an equation for the force, we have

$$C. F = \frac{2 T x}{1^2} = \frac{2 Q T^2}{2 S P} = \frac{S P^2 Q T^2}{S P^3} = \frac{h^2}{\text{Dist.}^3}$$
 if h = twice area described in 1".

110. *To compare the centripetal and centrifugal forces in any curve.*

Centripetal : centrifugal force :: Q R : T x ::

$$\frac{PQ}{PV} : \frac{QT}{2SP} :: \frac{SP}{PV} : \frac{SY}{2SP} \text{ (by similar } \triangle^s), ::$$

$$2SP : SY \times PV :: 2y^3 : p^3 \frac{2p dy}{dp} :: \frac{y^3}{p^3} : \frac{dy}{dp}$$

PROPOSITION VII.

Notes to Prop. 7.

111. In general, we have, as in Art. 88, the centripetal force $= \frac{8a^2 \times AV^2}{SP^2 \times PV^3}$, which is true for different \odot^s having the same or different centres of force.

112. If the centre of force S (*Fig. 64*) be without the circle, $\frac{1}{SP^2 \times PV^3}$, which expresses the law of the force, is positive, while the body moves from B through P to A ; but at A and B , PV vanishing, the force becomes infinite. From A through V and P' to B , PV lying the contrary way to what it did in the superior part of the orbit, the expression for the force becomes negative; the centre \therefore repels the body.

113. To prove the Prop. fluxionally, let SP (*Fig. 55*) $= y$, $PV = c$, $SY = p$, $PF = b$; then $PS \cdot SV = AS \cdot SB = \text{some constant quantity} = a^2$, *i. e.* $y \times c - y = a^2$, $\therefore c = \frac{a^2 + y^2}{y}$. Also by similar \triangle^s , $y : p :: b : \frac{a^2 + y^2}{y}$ $\therefore p = \frac{a^2 + y^2}{b}$ and $\frac{1}{p^2} = \frac{b^2}{a^2 + y^2}$. $\therefore \frac{dp}{p^3} = \frac{2b^2 y dy}{a^2 + y^2}$ and $\frac{dp}{p^3 dy} \propto \frac{b^2 y}{a^2 + y^2}$, $\propto \frac{y^2 \times \frac{b^2}{y^2}}{y^2 \times \frac{a^2 + y^2}{y^2}}$.

114. By Arts. 99 and 100, the velocity in the curve $= \frac{2a \cdot AV}{SP \cdot PV}$; and the velocity in the curve at P: velocity in \odot at same distance $:: \sqrt{\frac{1}{2} PV} : \sqrt{SP}$. If S be in the circumference of the \odot , the R° becomes that of $1 : \sqrt{2}$.

115. By Art. 110. Centripetal force : centrifugal $:: 2 SP \cdot AV^2 : PV^3$.

Notes to Prop. 7.—Cor. 2.

116. If the periodic times be not equal, then neither are the areas described in a given time round the two centres equal; \therefore in that case, F round S : F round R $\frac{SP}{SG^3}$
 $R :: \frac{P \cdot T \cdot \text{round } S}{P \cdot T \cdot \text{round } R} : \frac{S G^3}{P \cdot T \cdot \text{round } R}^2$; since AV^2 and the whole areas are the same in both cases.

117. Suppose R (*Fig. 65*) to be in the centre of the circle, and S to be at V in the circumference; to compare the forces round each centre, the periodic times being the same. Since the whole areas and periodic times are the same in both cases, $F \propto \frac{1}{SP^2 \cdot PV^3}$, \therefore F. round R : F. round V $:: \frac{1}{RP^2 \cdot PT^3} : \frac{1}{PV^3} :: \frac{1}{\frac{1}{4} PT^3} : \frac{1}{PV^3} :: PV^5 : \frac{1}{4} AV^5$.

PROPOSITION VIII.

Notes to Prop. 8.

118. Since $F \propto \frac{CP^2}{2PM^3 \times SP^2}$, and that SP^2 is infinite, it might be inferred that force was infinitely small; the contrary however will appear

from the general solution. For, in general, $F = \frac{8 a^3 Q R}{S P^2 Q T^2}$; but $V^2 = \frac{4 a^2}{S Y^2} \therefore a^2 = \frac{V^2 S Y^2}{4}$.
 Now let b = velocity in direction A C, which is constant, since the force in the direction of the ordinate does not affect the motion of the body in the direction of the abscissa, $\therefore V^2 : b^2 :: P R^2 : Q T^2 :: S P^2 : S Y^2 \therefore V^2 = \frac{b^2 S P^2}{S Y^2}$ and $a^2 = \frac{b^2 S P^2}{S Y^2} \times \frac{S Y^2}{4} = \frac{b^2 S P^2}{4} \therefore \frac{8 a^3 Q R}{S P^2 Q T^2} = \frac{C P^2}{2 P M^3 S P^2} \times \frac{8 b^3 S P^2}{4} = \frac{b^3 C P^2}{P M^3}$, a finite quantity when P M is finite.

119. By Art. 99, the velocity in the curve at P
 $= \frac{b \cdot C P}{P M}$.

120. By Art. 110, centripetal force at P : centrifugal $:: 2 S P^3 : S Y^2 \times P V :: 2 S P \times C P^2 : P M^2 \times P M$, *i. e.* centrifugal force is nothing, as also appears from the definition of a centrifugal force in Art. 106.

121. To find the fluxional expression for the law of the force, supposing this force to act in parallel lines.

Let A B (*Fig. 66*) = x , B P = y , P T = dx , T R = dy , b = velocity in the direction A B, which in the same curve will be constant, (Art. 118), v = velocity in the direction of the ordinate B P, and F = force in the direction P B; then $dx : dy :: b : v = \frac{b dy}{dx} \therefore dv = \frac{b d^2 y}{dx}$ and $v dv = \frac{b^2 dy d^2 y}{dx^2}$; but $-v dv = F dy \therefore F \times dy = -\frac{b^2 dy d^2 y}{dx^2}$ and $F = -\frac{b^2 d^2 y}{dx^2} \propto -\frac{d^2 y}{dx^2}$; or if P Q be an arc described in an indefinitely small *given* time dx is constant, and $F \propto -d^2 y$.

Or thus. By Prop. 6, $F \propto \frac{QR}{T^2 \dots PQ}$ but $T^2 \dots PQ$
 or $PT \propto \frac{PT^2}{b^2} \therefore F \propto \frac{QR \times b^2}{PT^2}$ or \propto
 $\frac{b^2 \times -d^2y}{dx^2}$ as before.

122. To prove the Prop. fluxionally, put $PM =$
 y , $CM = x$, $\therefore y = \sqrt{r^2 - x^2}$ and $dy = \frac{-x dx}{\sqrt{r^2 - x^2}} =$
 $\frac{x dx}{y}$
 $\frac{-x dx}{y}, \therefore d^2y = \frac{x dx dy - y dx^2}{y^2} = \frac{x dx \times \frac{x dx}{y} - y dx^2}{y^2}$
 $= \frac{-dx^2 \times x^2 + y^2}{y^3}, \therefore F \propto -\frac{d^2y}{dx^2}, \propto \frac{1}{y^3}.$

SCHOLIUM.

Introductory Article to Scholium.

123. *Lemma.*—Let PO (Fig. 67) be the diameter of curvature of the conic section DPL , C the centre, CD the $\frac{1}{2}$ conjugate diameter produced to meet PO in F , then will $PO \propto PA^3$.

For $CD \propto \frac{1}{PF} \therefore CD^2 \propto \frac{1}{PF^2}$ and $\frac{2CD^2}{PF}$
 or $PO \propto \frac{1}{PF^3}$; but by conics $PA \propto \frac{1}{PF} \therefore PA^3$
 $\propto \frac{1}{PF^3}$ and $PO \propto PA^3$.

Cor. If the distance betwixt the foci of the ellipse increase, PO still $\propto PA^3$; if \therefore this distance become infinite or the ellipse migrate into a parabola, $PO \propto PA^3$, and hence the Prop. is general.

Scholium.

124. Let L P D be any conic section, P V the chord of curvature perpendicular to the axis, then

$$\begin{aligned} & Q T^2 : P R^2 :: P M^2 : P A^2 \\ \therefore \frac{Q T^2}{Q R} & : \frac{P R^2}{Q R} \text{ or } P V :: P M^2 : P A^2 \end{aligned}$$

but $P V : P O :: P M : P A$

$$\begin{aligned} \therefore \frac{Q T^2}{Q R} : P O :: P M^3 : P A^3, \therefore \frac{Q T^2}{Q R} &= \frac{P O}{P A^3} \\ \times P M^3 \propto (\text{by Art. 123}) P M^3, \therefore \frac{S P^3 Q T^2}{Q R} &\propto \\ P M^3; \text{ and } F &\propto \frac{1}{P M^3}. \end{aligned}$$

The same fluxionally.

$$\begin{aligned} \text{In parabola } y^2 &= 2 a x, \therefore y dy = a dx \text{ and } \frac{dy}{dx} = \frac{a}{y} \\ \therefore -d^2 y &= \frac{a dy dx}{y^2} = \frac{a^2 dx^2}{y^3}, \therefore F \propto -\frac{d^2 y}{dx^2} \\ &\propto \frac{a^2}{y^3} \propto \frac{1}{y^3}. \end{aligned}$$

$$\begin{aligned} \text{In ellipse and hyperbola } y &= \frac{b}{a} \times \sqrt{a^2 - x^2}, \\ \therefore dy &= \frac{b}{a} \times \frac{-x dx}{\sqrt{a^2 - x^2}} = \frac{b}{a} \times \frac{-x dx}{\frac{a}{b} \times y} = \frac{b^2}{a^2} \\ &\times \frac{-x dx}{y}, \therefore d^2 y = \frac{b^2}{a^2} \times \frac{x dx dy - dx^2 y}{y^2} = \frac{b^2}{a^2} \\ &\times \frac{-\frac{b^2}{a^2} x^2 dx^2 - dx^2 y^2}{y^3} = \frac{-dx^2 \times \frac{b^2}{a^2} x^2 + y^2}{y^3}; \text{ but} \\ \text{since } y^2 &= \frac{b^2}{a^2} a^2 - x^2, \therefore \frac{b^2}{a^2} x^2 + y^2 = b^2, \therefore d^2 y \end{aligned}$$

$$\propto \frac{-dx^2 \times b^2}{y^3} \text{ and } F \propto -\frac{d^2y}{dx^2} \propto \frac{1}{y^3}$$

PROPOSITION IX.

Introductory Article to Proposition 9.

125. The curve which cuts all its radii, drawn from a fixed point, in a given \angle , is called the 'Equiangular Spiral.'

From this definition it follows, that the chord of curvature to any point of the spiral is double the radius vector at that point; for let S (*Fig. 70*) be the centre of the spiral, P Q an indefinitely small arc; from Q and P draw Q O, P O perpendicular to the curve at Q and P respectively, which will meet in O the centre of curvature; take P V the chord of curvature passing through S, and join V Q; then since the $\angle O Q A = \angle O P Q$, take from these the equal $\angle^s S Q A$, S P A, and the remainder the $\angle O Q S =$ the remainder the $\angle O P S$, and the \angle^s at C are vertical \angle^s , $\therefore \angle C O P = \angle Q S C$, but $\angle P O C$ being at the centre is double the $\angle P V Q$ at the circumference, \therefore also $\angle P S Q = 2 \angle P V Q$; but $\angle P S Q = \angle P V Q + \angle S Q V$, $\therefore \angle S V Q = \angle S Q V$, and S Q or S P = S V, $\therefore P V = 2 S P$.

Prop. 9.

126. *Case 1.* Let P Q, p q (*Fig. 71*) be two indefinitely small arcs, and let us suppose in the first place the $\angle P S Q$ to be a given \angle , i. e. that the $\angle P S Q = \angle p S q$, then since the \angle^s at S, P and R are respectively = the \angle^s at S, p and r, the remaining $\angle S Q R =$ remaining $\angle S q r$; \therefore the figures S Q R P

and $Sqr p$; $QRPT$ and $qrpt$; QPT and qpt ; SPQ and Spq are respectively similar to each other, and \therefore have their homologous sides proportional, \therefore

$$QT : qt :: QR : qr, \therefore \frac{QT}{QR} = \frac{qt}{qr} \text{ and } \frac{QT^2}{QR} : \frac{qt^2}{qr} :: QT : qt :: QP : qp :: SP : Sp, \therefore \frac{SP^2 \cdot QT^2}{QR} : \frac{Sp^2 \cdot qt^2}{qr} :: SP^3 : Sp^3 :: F. \text{ at } p : F. \text{ at } P.$$

Case 2. Suppose the $\angle PSQ$ not to be $= \angle pSq$; make in that case the $\angle PSS\pi = \angle pSq$,

then by the first case $\frac{\pi r^2}{\pi s} : \frac{qt^2}{qr} :: SP : Sp$; but

$$QR : \pi s :: QP^2 : \pi P^2, \text{ i. e. by similar } \Delta^s :: QT^2 : \pi r^2, \therefore \frac{\pi r^2}{\pi s} = \frac{QT^2}{QR} \therefore \frac{QT^2}{QR} : \frac{qt^2}{qr} :: SP : Sp$$

as in the first case; and this is the meaning of Newton's expression, "if the $\angle PSQ$ is in any way changed."

127. To prove the Prop. fluxionally put $SP = y$, $SY = p$; then $p : y$ in a given $R^\circ :: m : 1$, $\therefore p = \pi y$, and $\frac{1}{p^2} = \frac{1}{m^2 y^2}$, $\therefore \frac{4 a^2 dp}{p^3 dy} = \frac{4 a^2}{m^2 y^3} \propto \frac{1}{y^3}$.

128. By Arts. 99 and 100, the velocity in the curve $\propto \frac{1}{SP}$ and velocity in curve = velocity in a

○ at the same distance.

129. By Art. 110, centripetal force : centrifugal :: $SP^2 : SY^2 :: \text{rad.}^2 : \sin. \angle SPY^2$, and \therefore in a constant R° in the same spiral.

PROPOSITION X.*

Notes to Prop. 10.

130. To make the Prop. general, we have (Art. 88) $F = \frac{8 a^2 \times Q R}{S P^2 \times Q T^2} = \frac{4 a^2 \times P C}{A C^2 \times C B^2}$; which expression is general, and true for bodies moving round different centres.

131. If different bodies revolve round the *same* centre, then at equal distances the forces will be equal;

hence $\frac{4 a^2}{A C^2 \times C B^2}$ must be constant, \therefore when different bodies revolve round the same centre, the force $\propto C P$.

132. Let ϕ represent the absolute force, then accelerating force $= \phi \times P C = \frac{4 a^2}{A C^2 \times B C^2} \times P C$,

$$\therefore \phi = \frac{4 a^2}{A C^2 \times B C^2}.$$

* Table of Equations, containing the most common and useful properties of the Conic Sections:—

Parabola.

Latus rectum or $L = 4 S A$ (Fig. 16).

$T N = 2 A N$ (Fig. 82).

$S Y^2 = S P \cdot S A$ ($S Y = 1^{\text{st}}$ on tangent.)

$Q v^2 = 4 S P \cdot P v$ (Fig. 16).

$S P = \frac{2 A S}{1 + \cos. S}$, where $S = \angle$ traced out by radius vector.

Chord of curv. $= 4 S P$.

Diam. of curv. $= \frac{4 S P^{\frac{3}{2}}}{\sqrt{S A}}$.

Equation to the curve $y^2 = a x$ ($a = \text{latus rectum.}$)

133. To prove the Prop. fluxionally, put $a = \frac{1}{2}$ axis major, $b = \frac{1}{2}$ axis minor, $y = CP$, $p = PF =$ perpendicular on the tangent, then $p^2 = \frac{a^2 b^2}{a^2 + b^2 - y^2}$ and $\frac{1}{p^2} = \frac{a^2 + b^2}{a^2 b^2} - \frac{y^2}{a^2 b^2}$, $\therefore \frac{4 a^2 dp}{p^3 dy} = \frac{4 a^2 y}{a^2 b^2}$ and $F \propto y$.

Ellipse.

$SP + PH = 2 AC$ (Fig. 14.)

$AS \cdot SM = BC^2$.

$$L = \frac{2 BC^2}{AC}.$$

$$SY^2 = BC^2 \frac{SP}{PH}.$$

$$SP \cdot PH = CD^2.$$

$$AC^2 + CB^2 = CP^2 + CD^2.$$

$$AC \cdot CB = CD \cdot PF.$$

$$Q v^2 = \frac{P v \cdot v G \times CD^2}{CP^2}.$$

$$BC = a \sqrt{1 - e^2}, \text{ where } e = \text{eccentricity} = \frac{SC}{AC}.$$

$$SP = \frac{b^2}{a} \cdot \frac{1}{1 + e \cos. \vartheta} = \frac{a \cdot (1 - e^2)}{1 + e \cos. \vartheta}, \text{ where } \vartheta = \angle \text{traced out by } SP.$$

$$\text{Ch. curv. through } Cr. = \frac{2 CD^2}{CP}.$$

$$\text{Ch. curv. through focus} = \frac{2 CD^2}{AC}.$$

$$\text{Diam. of curv.} = \frac{2 CD^2}{PF}.$$

Equation to the curve $y^2 = \frac{b^2}{a^2} \cdot \overline{2ax - x^2}$, when the abscissa begins at the vertex.

Or $y^2 = \frac{b^2}{a^2} \cdot \overline{a^2 - x^2}$, when the abscissa begins at the centre

$$134. V = \sqrt{F \times \frac{P V}{2}} = \sqrt{\rho \cdot C P \times \frac{C D^2}{C P}} = \\ \sqrt{\rho \times C D^2} = \rho^{\frac{1}{2}} \times C D \propto (\text{round the same com-} \\ \text{mon centre}) C D.$$

135. Velocity in ellipse : velocity in \odot at the same distance :: $\sqrt{\frac{2 C D^2}{C P}} : \sqrt{2 C P} \therefore C D : C P.$

Cor. Hence the velocities in the ellipse and circle

Hyperbola.

$$H P - S P = 2 A C \text{ (Fig. 15).}$$

$$A S \cdot S M = B C^2.$$

$$L = \frac{2 B C^2}{A C}.$$

$$S Y^2 = B C^2 \cdot \frac{S P}{P H}.$$

$$S P \cdot P H = C D^2.$$

$$A C^2 - C B^2 = C P^2 - C D^2.$$

$$A C \cdot C B = C D \cdot P F.$$

$$Q v^2 = \frac{P v \cdot v G \times C D^2}{C P^2}.$$

$$B C = a \sqrt{e^2 - 1}.$$

$$S P = \frac{b^2}{a} \cdot \frac{1}{1 + e \cos. S} = \frac{a \cdot (e^2 - 1)}{1 + e \cos. S}.$$

$$Ch. \text{ curv. through cen.} = \frac{2 C D^2}{C P}.$$

$$Ch. \text{ curv. through focus} = \frac{2 C D^2}{A C}.$$

$$Diam. \text{ of curv.} = \frac{2 C D^2}{P F}.$$

$$y^2 = \frac{b^2}{a^2} \cdot \frac{2 a x + x^2}{2}, \text{ abscissa beginning at the vertex.}$$

$$\text{or } y^2 = \frac{b^2}{a^2} \cdot \frac{x^2 - a^2}{2}, \text{ abscissa beginning at the centre.}$$

at the same distance are equal in four points of the ellipse. For through the extremities of the major and minor axes (*Fig. 72*) of the ellipse draw tangents which will form a rectangle. Join $G C$, $H C$, which produced will pass through I and K , since $A F$ and $H K$, $A B$ and $H K$ are similar parallelograms, and \therefore about the same diameter; draw $B M$, which is bisected in L , consequently $B M$ is an ordinate to the diameter $P R$; also $B M$ is parallel to $H K$, $\therefore Q D$ is a conjugate diameter to $P R$; and since $\angle B C P = \angle B C D$, $C P = C D = C R = C Q$, \therefore the velocities in the ellipse and \odot at the points P , D , R , Q , are equal.

136. Centripetal force : centrifugal $:: P C^4 : A C^2 C B^2$. Hence these forces are equal when $P C^2 = A C$, $C B$, or when the distance from the centre is a mean proportional between the two $\frac{1}{2}$ axes of the ellipse. To find this point geometrically; from $C M$ (*Fig. 73*) cut off $C D = C B$; on $D A$ as diameter describe a $\frac{1}{2} \odot D E A$, produce $C B$ to meet it in E , and with C as centre and $C E$ as radius describe the $\odot P P'' E$; then will the centripetal force be = the centrifugal at the points P , P' , P'' , P''' ; for join $C P$ then $C P^2 (= C E^2 = A C \cdot C D) = A C$, $C B$, and the same may be proved of the other points.

Prop. 10.—Cor. 2.

$$\begin{aligned}
 137. \text{ Or thus, } P. T. &= \frac{\text{whole area}}{\text{area dat. temp.}} = \frac{\text{whole area}}{\frac{4}{a^2}}; \text{ but (Art. 132) } \varphi = \frac{A C^2 \times C B^2}{\pi \cdot A C \times B C} \therefore a \\
 &= \frac{A C \times C B}{2} \times \varphi \frac{1}{2} \therefore P. T. = \frac{\frac{1}{2} A C \times B C \times \varphi \frac{1}{2}}{\frac{2}{\varphi \frac{1}{2}}} \\
 &= \frac{2 \pi}{\varphi \frac{1}{2}}; \text{ i. e. } P. T. \text{ in all ellipses round the same} \\
 &\text{centre is constant, and about different } C^{\text{ns.}} \propto \frac{1}{\varphi \frac{1}{2}}.
 \end{aligned}$$

NOTES TO SECTION III.



PROPOSITION XI.

138. Or the Proportions may be thus arranged:—

$$Qv^2 : Pv.vG :: CD^2 : CP^2.$$

$$Pv : Px :: PC : PE \text{ or } AC$$

$$QT^2 : Qx^2 :: PF^2 : PE^2 \text{ or } AC^2$$

$$\therefore QT^2 : Px.vG :: CD^2.PF^2 : PC.AC^3$$

or $QT^2 : QR.2PC :: AC^2.BC^2 : PC.AC^3$

$$\therefore \frac{QT^2}{QR} = \frac{2BC^2}{AC} = L, \text{ and } \frac{QT^2.SP^2}{QR} = L.$$

$SP^2.$

PROPOSITIONS XI. XII. & XIII.

Notes to Props. 11, 12, and 13.

139. To make the above Props. general, we have
(Art. 88) the centripetal force $= \frac{8 a^2}{L \times S P^2}$, which
expression is general for bodies moving round different
centres of force.

140. If different bodies revolve in conic sections
round the *same* centre, then when they are at the
same distance from it, the forces will be equal, \therefore
 $\frac{8 a^2}{L}$ must be constant; consequently in this case the
force $\propto \frac{1}{S P^2}$.

141. Let ϕ represent the absolute force, then ac-
celerating force $= \frac{\phi}{S P^2} = \frac{8 a^2}{L \times S P^2}$, $\therefore \phi = \frac{8 a^2}{L}$,
and $a^2 = \frac{L \cdot \phi}{8}$.

142. To prove the Prop. fluxionally, we have in
the ellipse $p^2 = b^2 \times \frac{y}{2 a - y}$; in the hyperbola p^2
 $= b^2 \times \frac{y}{2 a + y}$; and in the parabola $p^2 = a y$;
 \therefore (1) $\frac{1}{p^2} = \frac{2 a}{b^2 y} - \frac{1}{b^2}$; (2) $\frac{1}{p^2} = \frac{2 a}{b^2 y} + \frac{1}{b^2}$; (3)
 $\frac{1}{p^2} = \frac{1}{a y}$, $\therefore F = \frac{4 a^2 dp}{p^3 dy} =$ (in all the three cases)
 $\frac{8 a^2}{L \times y^2}$.

PROPOSITION XIV.

Note to Prop. 14.

143. This Prop. is only applicable to different bodies moving round the *same* common centre. To make it general, we have $L = \frac{Q T^2}{Q R}$, but (Art. 88) $Q R = \frac{F}{2}$ when the time is given, $= \frac{\phi}{2 S P^2} \therefore L = \frac{2 S P^2 \times Q T^2}{\phi} = \frac{8 a^2}{\phi}$. The same conclusion was obtained in Art. 141.

Note to Prop. 14.—Cor.

144. If bodies revolve in ellipses round different centres, we have $A = P. a = P. \sqrt{\frac{L \phi}{8}} \therefore A C. C B \propto L^{\frac{1}{2}}. \phi^{\frac{1}{2}}. P$.

PROPOSITION XV.

Note to Prop. 15.

145. This Prop. is only applicable to different bodies moving round the same common centre. To make it general, $P. T = \frac{A}{a}$, but (Art. 141) $a^2 = \frac{L. \phi}{8} = \frac{B C. \phi}{4 A C}$; $\therefore a = \frac{B C. \sqrt{\phi}}{2 \sqrt{A C}}$, $\therefore P. T = \frac{A}{a} = \frac{\pi. A C. B C}{a} = \frac{2 \pi A C^{\frac{3}{2}}}{\sqrt{\phi}}$.

PROPOSITION XVI.

Note to Prop. 16.

146. This Prop. is only true for different bodies moving round the same common centre; to make it

$$\text{general we have } V = \frac{S P \cdot Q T \cdot 2 a}{S Y} = \frac{\sqrt{\phi L}}{\sqrt{2} \cdot S Y}$$

which is applicable to bodies moving round different centres of force.

Prop. 16.—Cor. 4.

$$\begin{aligned} 147. \text{ For } V^2 : v^2 :: \frac{L}{BC^2} : \frac{2 AC}{AC^2} :: L : \frac{2 BC^2}{AC} \\ :: L : L :: 1 : 1; \text{ and } \therefore \text{ since the velocities in } \odot^* \propto \\ \frac{1}{\sqrt{\text{dist.}}}, \text{ the velocities of bodies revolving in ellipses} \\ \text{round a common centre will at the mean distance } \propto \\ \frac{1}{\sqrt{\text{dist.}}} \end{aligned}$$

Prop. 16.—Cor. 6.

$$\begin{aligned} 148. \text{ For in different points of the same curve } V \propto \\ \frac{1}{S Y}; \therefore \text{ in parab. } V \propto \frac{1}{S Y} \propto \frac{1}{\sqrt{S P}}; \text{ in the ellipse} \\ \text{and hyperbola } V \propto \frac{1}{S Y} \propto \frac{1}{BC \sqrt{\frac{S P}{P H}}} \propto \sqrt{\frac{H P}{S P}}. \end{aligned}$$

Now in the ellipse, as $S P$ or the denominator of this fraction increases or decreases, $H P$ or the numerator decreases or increases; consequently the fraction

$\frac{HP}{SP}$ will vary more than the fraction $\frac{1}{SP}$, and \therefore

the velocity will vary in a higher R^o. than $\frac{1}{\sqrt{SP}}$;

but in the hyperbola, as SP increases or decreases, HP also increases or decreases; consequently the

fraction $\frac{HP}{SP}$ varies less than the fraction $\frac{1}{SP}$, i. e.

the velocity varies in a less R^o. than $\frac{1}{\sqrt{SP}}$.

Prop. 16.—Cor. 7.

149. For in the parabola $V^2 : v^2 :: \frac{4SA}{SP \cdot SA} : \frac{2SP}{SP^2} :: 2 : 1$, $\therefore V : v :: \sqrt{2} : 1$.

In the ellipse $V^2 : v^2 :: \frac{\frac{2BC^2}{AC}}{BC^2 \cdot \frac{SP}{PH}} : \frac{2SP}{SP^2} ::$

$HP : AC$, $\therefore V : v :: \sqrt{HP} : \sqrt{AC} :: \sqrt{2AC - SP} : \sqrt{AC} :: \sqrt{2 - \frac{SP}{AC}} : 1 :: \sqrt{2} - 1$.

In hyperbola $V : v :: \sqrt{HP} : \sqrt{AC} :: \sqrt{2AC + SP} : \sqrt{AC} :: \sqrt{2 + \frac{SP}{AC}} : 1 :: \sqrt{2} + 1$.

Hence also velocity in parabola = velocity in \odot at $\frac{1}{2}$ the distance. For

$$\begin{aligned} V : v &:: \sqrt{2} : 1 \\ \& v : \text{velocity in } \odot \text{ r. } \frac{1}{2} SP &:: 1 : \sqrt{2} \\ \therefore V = \text{velocity in } \odot \text{ radius } \frac{1}{2} SP & \end{aligned}$$

$$\begin{aligned}
 &\text{But in ellipse } V : v :: \sqrt{2-} : 1 \\
 &\& v : v. \text{ in } \odot r. \frac{1}{2} SP :: 1 : \sqrt{2-} \\
 \hline
 &\therefore V : v. \text{ in } \odot r. \frac{1}{2} SP :: \sqrt{2-} : \sqrt{2-} \\
 &\therefore V \text{ is less than velocity in } \odot r. \frac{1}{2} SP
 \end{aligned}$$

$$\begin{aligned}
 &\text{And in hyperbola } V : v :: \sqrt{2+} : 1 \\
 &\& v : \text{velocity in } \odot r. \frac{1}{2} SP :: 1 : \sqrt{2+} \\
 \hline
 &\therefore V : \text{velocity in } \odot r. \frac{1}{2} SP :: \sqrt{2+} : \sqrt{2+} \\
 &\therefore V \text{ is greater than velocity in } \odot r. \frac{1}{2} SP.
 \end{aligned}$$

Prop. 16.—Cor. 8 and 9.

¶ 50. For let V = velocity in the conic section at the distance SP ; v = velocity in a \odot at the distance of $\frac{1}{2}$ the *latus rectum*; and v' = velocity in a \odot at the distance SP ; then since the *latera recta* in the conic section and first \odot are equal

$$V : v :: \frac{1}{2} L : SY, \text{ which is the 8th Corollary.}$$

$$\text{Again } v : v' :: \sqrt{SP} : \sqrt{\frac{1}{2}L},$$

$$\therefore V : v' :: \sqrt{\frac{1}{2}L \times SP} : SY, \text{ which is the 9th Corollary.}$$

DEDUCTIONS FROM THE PRECEDING PART OF THIS SECTION.

¶ 51. *Of the LINEAR velocities of bodies revolving in conic sections, the centre of force being in the focus.*

1. *Required a general expression for the velocities of bodies revolving in any of the conic sections.*

$$(1) \text{ In parabola } V^2 = F \times \frac{1}{2} PV = \bar{S}^{\phi} P^2 \times 2SP$$

$$= \frac{2\phi}{SP}, \therefore V \propto \frac{\phi^{\frac{1}{2}}}{SP^{\frac{1}{2}}}.$$

(2) In ellipse and hyperbola $V^2 = F \times \frac{1}{2} PV =$
 $\frac{\phi}{SP^2} \times \frac{SP \cdot PH}{AC} = \frac{\phi \times PH}{AC \cdot SP}, \therefore V = \sqrt{\frac{\phi \times PH}{AC \cdot SP}}.$

Or the same may be deduced from Art. 146, by substituting for L and SY in the Equation $V = \frac{L^{\frac{1}{2}} \times \phi^{\frac{1}{2}}}{\sqrt{2} SY}$.

Cor. 1. If different bodies revolve round the same centre, ϕ is constant; \therefore in parabola $V \propto \frac{1}{\sqrt{SP}}$;

and in ellipse and hyperbola $V \propto \sqrt{\frac{HP}{AC \cdot SP}}.$

Cor. 2. In different points of the same curve we have in parabola $V \propto \frac{1}{\sqrt{SP}}$; and in ellipse and hyperbola $V \propto \sqrt{\frac{HP}{SP}}.$

2. *To compare the velocity in a conic section with the velocity in a circle at the same distance.*

$$V \propto \sqrt{PV}, \therefore \text{velocity in conic section} : \text{velocity in } \odot \text{ at same distance} :: \sqrt{\frac{2CD^2}{AC}} : \sqrt{2SP} :: \sqrt{\frac{2SP \cdot PH}{AC}} : \sqrt{2SP} :: \sqrt{HP} : \sqrt{AC}.$$

Or the same may be demonstrated as in Prop. 16, *Cor. 7.*

Cor. 1. Hence velocity in ellipse = velocity in a

⊙ at the mean distance ; for in that case $HP = AC$; the same is also shewn in Prop. 16, Cor. 4.

Cor. 2. Hence also the same conclusions may be deduced as those given in Prop. 15, Cor. 7.

3. *To compare the velocity in any point of the ellipse with the velocity at the mean distance.*

$$V \propto \frac{1}{SY}, \therefore \text{velocity in ellipse : velocity at mean distance} :: \frac{1}{CB \sqrt{\frac{SP}{PH}}} : \frac{1}{CB} :: \sqrt{HP} : \sqrt{SP}.$$

4. *If a body revolve in an ellipse ; required the point where the velocity is an arithmetic mean between the greatest and least velocities.*

Let D and δ = greatest and least distances p = perpendicular upon the tangent at the required point ; then by the Prob. $\frac{1}{D} + \frac{1}{\delta} = \frac{2}{p}$, $\therefore p = \frac{2 D \delta}{D + \delta} =$

$$\frac{b^2}{a} = \frac{1}{2} L, \text{ or at the required point the perpendicular} = \frac{1}{2} \text{ the latus rectum ; to find when this is the case we have } p = \frac{b^2}{a} = b \times \sqrt{\frac{x}{2a-x}}, \therefore \frac{b^4}{a^2} = \frac{b^2 x}{2a-x}, \therefore x = \frac{2 a b^2}{a^2 + b^2}.$$

5. *Required the same when the velocity is a geometric mean between the greatest and least velocities.*

$$\text{Here } \frac{1}{D} \times \frac{1}{\delta} = \frac{1}{p^2}, \therefore p^2 = D \delta = b^2 \text{ and } p = b;$$

i. e. the required point is at the extremity of the minor axis, or at the mean distance.

6. *Required the same when the velocity is an harmonic mean between the greatest and least velocities.*

Here by Prob. $\frac{1}{D}$, $\frac{1}{p}$ and $\frac{1}{\delta}$ are in harmonical progression, $\therefore D$, p and δ will be in arithmetical progression $\therefore 2p = D + \delta$ and $p = \frac{D + \delta}{2} = a$. If the distance be required at this point, we have $\frac{b^2 x}{2a - x} = p^2 = a^2 \therefore x = \frac{2a^3}{a^2 + b^2}$

7. *Required the point in the parabola, where the decrement of the linear velocity is a maximum.*

By pursuing the method given, (Art. 104) we have $v \propto \frac{1}{p} \propto y^{-\frac{1}{2}}$, $\therefore dv \propto \frac{dy}{y^{\frac{3}{2}}}$; but by that Art. $dy = \frac{\sqrt{y^2 - p^2}}{py} = \frac{\sqrt{y^2 - ay}}{a^{\frac{1}{2}} y^{\frac{3}{2}}} = \frac{\sqrt{y - a}}{a^{\frac{1}{2}} y}$, $\therefore dv \propto \frac{\sqrt{y - a}}{y^{\frac{5}{2}}}$ which is a maximum by Prob.; $\therefore \frac{y - a}{y^5}$ or $\frac{1}{y^4} - \frac{a}{y^5}$ is a maximum, $\therefore \frac{4dy}{y^5} - \frac{5a dy}{y^6} = 0$, or $y = \frac{5a}{4}$.

8. *Required the same in the ellipse.*

$v \propto \frac{1}{p} \propto \sqrt{\frac{2a - y}{y}} \propto \sqrt{\frac{2a}{y}} - 1$, $\therefore dv \propto \frac{2a - y}{y^{\frac{3}{2}}} \times \frac{2a dy}{y^{\frac{3}{2}}} \propto \frac{2a dy}{y^{\frac{3}{2}} \sqrt{2a - y}}$; but $dy = \frac{\sqrt{y^2 - p^2}}{py} =$

$$\frac{\sqrt{y^2 - \frac{b^2 y}{2a-y}}}{by \sqrt{\frac{y}{2a-y}}} = \frac{\sqrt{2ay - y^2 - b^2}}{by}, \therefore dv \propto \frac{\sqrt{2ay - y^2 - b^2}}{y^{\frac{5}{2}} \sqrt{2a-y}} = \text{maximum}, \therefore \frac{2ay - y^2 - b^2}{y^5 \cdot 2a-y} \text{ or } \frac{1}{y^4} - \frac{b^2}{y^5 \cdot 2a-y} = \text{maximum}, \therefore \frac{4dy}{y^5} - \frac{10ab^2y^4 dy - 6b^2y^5 dy}{y^{10} \times (2a-y)^2} = 0; \text{ or } 2y^3 - 8ay^2 + 8a^2 + 3b^2 \cdot y - 5ab^2 = 0; \text{ from whence } x \text{ may be found.}$$

9. Required the point in the parabola, where the paracentric velocity is a maximum.

By Art. 103, Paracentric velocity $\propto \frac{\sqrt{y^2 - p^2}}{py}$,
 \therefore in this case $\propto \frac{\sqrt{y^2 - ay}}{a^{\frac{1}{2}} y^{\frac{3}{2}}} = \text{maximum}, \therefore \frac{y^2 - ay}{y^3}$
or $\frac{1}{y} - \frac{a}{y^2} = \text{maximum}, \therefore y = 2a$, i. e. the required point is at the extremity of the *latus rectum*.

10. Required the same in the ellipse and hyperbola.

Paracentric velocity $\propto \frac{\sqrt{y^2 - p^2}}{py}$, which by Prob.
is a maximum, $\therefore \frac{y^2 - p^2}{p^2 y^2}$ or $\frac{1}{p^2} - \frac{1}{y^2} = \text{maximum}$,
i. e. $\frac{2a+y}{b^2 y} - \frac{1}{y^2}$, or $\frac{2a}{b^2 y} + \frac{1}{b^2} - \frac{1}{y^2} = \text{maxi-}$

mum, $\therefore y = \frac{b^2}{a} = \frac{1}{2}$ latus rectum.

152. *Of the ANGULAR velocities of bodies revolving in the conic sections ; force tending to the focus.*

1. *Required a general expression for the angular velocity of bodies revolving in any of the conic sections.*

Let a = area described in a given time, then \angle^r velocity $\propto \frac{a}{S P^2} \propto \frac{L^{\frac{1}{2}} \times \phi^{\frac{1}{2}}}{S P^2}$.

Cor. 1. If different bodies revolve round the same centre, ϕ is constant, $\therefore \angle^r$ velocity $\propto \frac{L^{\frac{1}{2}}}{S P^2}$.

Cor. 2. In different points of the same curve \angle^r velocity $\propto \frac{1}{S P^2}$.

2. *To compare the \angle^r velocity in a conic section with the \angle^r velocity in a \odot at the same distance.*

\angle^r velocity $\propto \frac{L^{\frac{1}{2}}}{S P^2} \propto$ (since the distance is the same) $L^{\frac{1}{2}}$, $\therefore \angle^r$ velocity in the conic section : \angle^r velocity in a \odot at the same distance $:: L^{\frac{1}{2}} : \overline{S P}^{\frac{1}{2}}$
 $\frac{1}{2} L^{\frac{1}{2}} : \overline{S P}^{\frac{1}{2}}$.

Cor. Hence \angle^r velocity in the conic section = \angle^r velocity in \odot at the same distance at the extremity of the latus rectum.

3. *To compare the \angle^r velocity in any point of the ellipse with the mean \angle^r velocity.*

If a circle be described with the focus of the ellipse

as centre, and radius = A C or mean distance, the periodic time in this circle will = the periodic time in the ellipse, hence the uniform \angle^r velocity in this \odot will represent the mean \angle^r velocity of the body

in the ellipse; \therefore since \angle^r velocity $\propto \frac{L^{\frac{1}{2}}}{S P^2}$, we have

\angle^r velocity in any point P : mean \angle^r velocity (or \angle^r velocity in \odot radius = mean distance) ::

$$\frac{\sqrt{\frac{2 C B^2}{A C}}}{S P^2} : \frac{\sqrt{\frac{2 A C}{A C^2}}}{A C^2} :: \frac{1}{S P^2} : \frac{1}{A C \cdot C B}$$

Cor. Hence the \angle^r velocity in the ellipse = mean \angle^r velocity when $S P^2 = A C \cdot C B$, or when the distance from the focus is a mean proportional between the $\frac{1}{2}$ axes of the orbit.

4. To compare the \angle^r velocity at the mean distance with the mean \angle^r velocity.

\angle^r velocity at mean distance : mean \angle^r velocity ::

$$\frac{\sqrt{\frac{2 C B^2}{A C}}}{A C^2} : \frac{\sqrt{\frac{2 A C}{A C^2}}}{A C^2} :: C B : C A.$$

Cor. Hence the \angle^r velocity at the mean distance is less than the mean \angle^r velocity.

5. The \angle^r velocity round the higher focus of an ellipse of small eccentricity is nearly uniform.

Take P p (Fig. 74) an indefinitely small arc, join P S, p S, and P H, p H; from P draw P n perpendicular to S p produced, and P m perpendicular to H p; then because the \angle P p m = \angle S p B = \angle P p n, and that the \angle^s at n and m are right \angle^s and P p common, \therefore P n = P m; Hence \angle^r velocity round S : \angle^r velocity round

153. *Of Centripetal and Centrifugal Forces in the Conic Sections, the centre of force being in the focus.*

1. *Required a general expression for the centrifugal force in the conic sections.*

Let a = area described in a given time, then Art. 109, Cor. 2, centrifugal force $= \frac{4 a^2}{S P^3} = \frac{L \cdot \phi}{2 S P^3}$.

Cor. 1. If different bodies revolve round the same centre, ϕ is constant, \therefore the centrifugal force $\propto \frac{L}{S P^3}$.

Cor. 2. In different points of the same curve, centrifugal force $\propto \frac{1}{S P^3}$.

2. *To compare centripetal and centrifugal forces in the conic sections.*

(1) In parabola; centripetal force : centrifugal $:: 2 S P^3 : S Y^2 \times P V :: S P : 2 S A :: S P : \frac{1}{2} L$.

(2) In ellipse and hyperbola; centripetal force : centrifugal $:: 2 S P^3 : S Y^2 \cdot P V :: 2 S P^3 : B C^2 \times \frac{S P}{P H} \times \frac{2 S P \cdot P H}{A C} :: S P : \frac{B C^2}{A C} :: S P : \frac{1}{2} L$.

Cor. Hence centripetal force = centrifugal at the extremity of the *latus rectum*.

3. *Force in any conic section : force in circle at the same distance, and moving with the same \angle^r velocity $:: S P : \frac{1}{2} L$.*

For by Art. 139, force $\propto \frac{a^2}{L \times S P^2} \propto$ (since the \angle^r velocity and distance, and consequently a are

the same in both cases) $\frac{1}{L}$, \therefore force in conic section :
 force in \odot at same distance, and moving with the
 same \angle^r velocity $:: \frac{1}{L} : \frac{1}{2 SP} :: SP : \frac{1}{2} L$.

Or the same may be deduced from the last Example; for the force in the \odot at the same distance, and moving with the same \angle^r velocity, is equal to the centrifugal force in the curve, but it has been shewn that centripetal force : centrifugal $:: SP : \frac{1}{2} L$, \therefore &c.

MISCELLANEOUS PROBLEMS TO THE TWO LAST SECTIONS.

1. *If the 4th power of the periodic times in different \odot s are as the cube of the velocities, find how the force, periodic time, and velocity vary in terms of radius.*

$$P^4 \propto V^3, \therefore P^2 \propto V^{\frac{3}{2}}, \text{ and } \frac{R}{P^2} \text{ or } \frac{V^2}{R} \propto \frac{R}{V^3},$$

$$\therefore V \propto R^{\frac{4}{7}}.$$

$$\text{Again, } P^2 \propto V^{\frac{3}{2}} \propto R^{\frac{6}{7}}, \text{ and } P \propto R^{\frac{3}{7}}.$$

$$\text{Lastly, } F \propto \frac{R}{P^2} \propto R^{\frac{1}{7}}.$$

2. *Find the actual velocity and periodic time of a body revolving at the distance of two of the earth's radii above its surface.*

$$V = \sqrt{F \cdot R} = \sqrt{g \cdot \frac{1^2}{3^2} \cdot 3r} = \sqrt{\frac{g r}{3}}.$$

$$\text{Also } P = \frac{2\pi \cdot 3r}{v} = \pi \sqrt{\frac{108r}{g}}.$$

3. *Given the force of gravity on the earth's surface, and the moon's periodic time; to find her distance.*

Let x = distance then as before

$$V = \sqrt{g \cdot \frac{r^2}{x^2}} = \sqrt{\frac{g r^2}{x}}; \text{ and } P = \frac{2\pi x}{v},$$

$$\therefore x = \left(\frac{g P^2 r^2}{4\pi^2} \right)^{\frac{1}{3}}$$

4. A body is revolving in a given \odot about its centre, if the absolute force be increased in a given R^o , what must be the change of velocity that the body may still describe the same circle ?

Let force before change : force after $:: 1 : n$;

then since $V \propto \phi^{\frac{1}{2}}$ when R is given,

V. before change : V. after $:: 1 : \sqrt{n}$.

5. What must be the law of the force, that the areas dat. temp. in all \odot^s uniformly described about the centre of force, may be equal ?

$$P \propto \frac{A}{a} \propto (\text{by Prob.}) A \propto R^2 ;$$

$$\therefore F \propto \frac{R}{P^2} \propto \frac{1}{R^3}.$$

6. Let the magnitude of a planet : magnitude of earth $:: n : 1$, and their densities as $1 : p$; required the space fallen through in 1" at the surface of the planet.

$$\text{Here } F \propto \frac{Q^v \text{ of matter}}{r^2} \propto \frac{\text{magnitude} \times \text{density}}{r^2}$$

$$\propto \text{density} \times r \propto \text{density} \times \sqrt[3]{\text{magn}^e}.$$

$$\therefore F : \text{gravity } (g) :: \sqrt[3]{n} \times 1 : \sqrt[3]{1} \times p,$$

$$\therefore F = \frac{g \sqrt[3]{n}}{p} \text{ and } S = \frac{F \cdot T^2}{2} = \frac{g \sqrt[3]{n}}{2 p}.$$

7. Required the Ratio of the quantities of matter in planets which have secondaries revolving round them.

Let ϕ = absolute force = quantity of matter in primary ; $D = \frac{1}{2}$ axis of the ellipse described by the secondary, or = mean distance of the secondary

from the primary, P = periodic time of the secondary;

$$\text{then by Art 145, } P^2 \propto \frac{D^3}{\varphi} \therefore \varphi \propto \frac{D^3}{P^2};$$

φ may \therefore be assumed $= \frac{D^3}{P^2}$; from whence we shall get the quantity of matter of the several planets in proportional numbers.

8. *Required the Ratio of the densities of planets which have secondaries revolving round them.*

Let r = radius of primary, s = sin. of the \angle under which r appears at the distance D to radius unity; then since density $\propto \frac{\text{quan. } M^r}{\text{magni.}}$, we have density \propto

$$\frac{\varphi}{r^3} \propto \frac{D^3}{P^2 \cdot r^3}; \text{ but } \frac{r^3}{D^3} = s^3, \therefore \text{density} \propto \frac{1}{P^2 \cdot s^3};$$

assume \therefore density $= \frac{1}{P^2 \cdot s^3}$, and we shall get the density of the planets in proportional numbers.

9. *Required the Ratio of the weights of equal bodies on the surfaces of planets having secondaries revolving round them.*

The weight of any body \propto quantity of matter \times accelerating force; \therefore since the bodies are equal by supposition, the weight will be as the force with which the planets attract it,

$$\text{i. e. weight} \propto \frac{\varphi}{r^2} \propto \frac{D^3}{P^2 \cdot r^2}.$$

This will also give the R^o of the spaces fallen through in 1" at the surface of the planets; for space \propto accelerating force, when the time is given.

Note.—The density, &c. of planets, which have not

satellites revolving round them, can only be found by observing the effects which those planets produce upon the other planets in disturbing their motion.

10. *Having given the quantities of matter of the earth and moon and their distance ; find that point between them at which a body would be at rest.*

Let a = distance of earth and moon, x = distance from the moon where the attractions are equal, Q and q the quantities of matter ;

$$\text{Then } \frac{q}{x^2} = \frac{Q}{(a-x)^2}, \text{ or } \frac{\sqrt{q}}{x} = \frac{\sqrt{Q}}{a-x},$$

$$\therefore x = a \cdot \frac{\sqrt{q}}{\sqrt{Q} + \sqrt{q}}.$$

11. *Supposing the earth and moon to be of equal densities, and diameter of earth : diameter of moon :: 4 : 1 ; shew that the point of equal attraction between the earth and moon divides the distance between their centres in the R^o of 8 : 1.*

Let R and r be the radii of the earth and moon, D and δ the distances of the point of equal attraction from each ; then

$$\frac{Q}{D^2} = \frac{q}{\delta^2},$$

$$\therefore D^2 : \delta^2 :: Q : q ;$$

but when densities are equal,

$$Q : q :: R^3 : r^3 :: 64 : 1,$$

$$\therefore D : \delta :: 8 : 1.$$

12. *If the attraction of the earth and moon be as their quantities of matter directly and the squares of their distances inversely ; what is the nature of the curve in which a body being placed would be equally attracted to both ?— (Fig. 74 a)*

Let E be the earth, M the moon ; A the point de-
U

terminated, Prob. 10, where the attraction to both bodies is equal, A lying immediately between E and M.

Put $EA = b$, $MA = a$, $AN = x$, $PN = y$;

Then $\frac{Q}{EP^2} = \frac{q}{PM^2}$ or $\frac{Q}{b+x)^2 + y^2} = \frac{q}{a-x)^2 + y^2}$.

$$\therefore Q - q \cdot y^2 = q b^2 - Q a^2 + Q \overline{a + q b} \cdot 2x - Q - q \cdot x^2;$$

$$\text{but } \frac{Q}{b^2} = \frac{q}{a^2} \text{ or } Q a^2 = q b^2,$$

$$\therefore Q - q \cdot y^2 = Q \overline{a + q b} \cdot 2x - Q - q \cdot x^2,$$

$$\therefore y^2 = \frac{Q a + q b}{Q - q} \cdot 2x - x^2,$$

\therefore the curve is a circle.

Cor. 1. If the $\frac{1}{2} \odot$ revolve round the diameter ACB , it will generate a sphere, in every point of which a body being placed, will be equally attracted to both bodies.

Cor. 2. The radius of the sphere $= \frac{Q a + q b}{Q - q}$,
and $AM = a$.

$\therefore MC = \frac{Q a + q b}{Q - q} - a =$ distance of the
centre of the sphere from the moon's centre.

Cor. 3. $\frac{Q a + q b}{Q - q} + b = \frac{Q}{Q - q} \cdot \overline{a + b} =$
 EC ;

hence $\frac{Q}{Q - q} \cdot \overline{a + b} : \frac{Q a + q b}{Q - q} :: Q : \overline{a + b}$

$: Q a + q b :: 1 : \cos. ACD,$

$\therefore DCF = 2 ACD$ is known.

13. Having given the relation between the centrifugal force and the force of gravity at the earth's equator; deter-

mine the relation between the centrifugal force and the force of gravity at the equator of Jupiter, the densities and times of revolution round their axes being known.

Let D and δ be the densities of Jupiter and the earth, P and p their times of revolution round their axes, and let centrifugal force of earth : gravity :: $n : 1$;

then since centrifugal force $= \frac{R}{P^2}$ and gravity

$$\propto \frac{D \cdot R^3}{R^2} \propto D \cdot R,$$

$$\frac{F}{G} \propto \frac{1}{P^2 D};$$

$$\therefore \frac{F}{G} \text{ in case of Jupiter} : \frac{F}{G} \text{ in earth} = \frac{n}{1}$$

$$\therefore p^2 \delta : P^2 D,$$

$$\text{and } F : G :: n p^2 \delta : P^2 D.$$

14. The earth being supposed a sphere revolving about its axis with a given \angle^r velocity ; find the point in the plane of the equator where the centripetal force = the centrifugal.

Let Pp be the earth's axis (Fig. 68), EC the equator, A the required point ; put $CA = x$, $CE = r$, $P =$ time of the earth's revolving on its axis, $p =$ P. T. of a body revolving at the earth's surface, then

$$\text{centripetal force at } E : \text{centrifugal at } E :: P^2 : p^2$$

$$\text{centrifugal force at } E : \text{centrifugal at } A :: r : x$$

$$\text{centripetal force at } A : \text{centripetal at } E :: r^2 : x^2$$

$$\therefore \text{centripetal force at } A : \text{centrifugal at } A :: P^2 r^2 : p^2 x^2,$$

$$\therefore \text{by Prob. } p^2 x^2 = P^2 r^2, \text{ and } x = r \cdot \sqrt{\frac{P}{p}}.$$

15. *The same things being supposed ; find the curve in a meridional plane which is the locus of a body, the centrifugal force of which, opposed to gravity, is every where equal to the force of gravity acting upon it.*—(Fig. 68.)

Let A be the point in the plane of the equator where centripetal force = centrifugal (see last Prob.), M any other point in the meridional plane ; put $CN = x$, $MN = y$, $CA = a$; then

centrif. force at A : centrif. at M (or MB) :: $a : y$

MB : MD (opposed to grav.) :: $\sqrt{x^2 + y^2} : y$

centrip. force at M : centrip. at A :: $a^2 : x^2 + y^2$

∴ centrip. force at M : MD :: $a^3 : y^2 \sqrt{x^2 + y^2}$,

∴ by Prob. $y^2 \sqrt{x^2 + y^2} = a^3$;

an equation belonging to a curve of the 5th order, having two infinite legs, to which Pp produced is an asymptote.

16. *In the 10th Lemma, where AD represents the time, DB the velocity, and ABD the space described ; if a straight line be drawn touching the curve AB in B the extremity of the ordinate, the tangent of the ∠ which this line makes with the axis will represent the force.*

$F = \frac{dv}{dt} = (\text{Fig. 29}) \frac{GF}{BG} = \tan. \angle FBG = \tan. \angle BED.$

17. *If a body begins to roll from B (Fig. 77) down the quadrant BPD, with the velocity acquired in falling through the given space AB ; to determine the point where it will leave the quadrant, and the point where it will meet the horizontal plane.*

When the body leaves the quadrant it will describe

a parabola, let it leave the circle in P; then P is a point both in the parabola and circle, and PBD is a circle of curvature to the parabola at P, since $PV \propto \sqrt{F}$; hence velocity at P = velocity acquired in falling down $\frac{1}{4}$ of the chord of curvature or $\frac{1}{2} PF$; but it also = velocity down $AB + BE$;

$$\therefore AB + BE = \frac{PF}{2} = \frac{BC - BE}{2};$$

$$\therefore BE = \frac{BC - 2AB}{3} = \text{vers. sin. of arc described.}$$

Again, from A draw AN parallel to the horizon, which line is the directrix of the parabola Pp; make $\angle SPx = \angle N Px$, and $PS = PN$, and S is the focus; with S as centre and AC as radius, describe a circle cutting the horizontal line Cp in p; p is the point required. For $Sp = CA = po$; $\therefore p$ is a point in the parabola.

Cor. If $AB = \frac{1}{2} BC$, $BE = 0$, or the body will fly off in a tangent at B; if AB be greater than $\frac{1}{2} BC$, then BE is negative, i. e. ver. sin. is negative, or the Prob. is impossible.

18. Suppose a body to begin to move from the point C (Fig. 78) of the cycloid ACP; to find the point where the body will leave the curve.

Let P be the point required; then as before (since $PF = \frac{1}{4}$ chord of curvature of cycloid, and \therefore of parabola since $PV \propto \sqrt{F}$;) PF or $ED = BE$, i. e. $AD - AE = AE - AB$, $\therefore AE = \frac{AD + AB}{2}$.

19. *If any number of bodies be retained in horizontal circular orbits by means of strings of unequal lengths, and the distance of the centres from the point of suspension be equal; the times of their revolutions will be the same.*

This immediately appears from Art. 84, Ex. 4; for it is there shewn that $P. T. \propto \sqrt{SA}$.

20. *A body whirled round by a string CA (Fig. 79.) in a vertical plane just keeps the string extended at A; required the proportion of the tension of the string at B to the weight of the body.*

By the Prob. the centrifugal force at A is just = the weight of the body, and \therefore the velocity at A is = that acquired in falling through DA = $\frac{AC}{2}$; also the velocity at B = that acquired through DA + AB or $\frac{5AC}{2}$; \therefore since centrifugal force $\propto V^2$, when r is given, *i. e.* \propto space fallen through;
centrifugal force at B : centrifugal force at A,
or weight of the body, $\therefore 5 : 1$;
but the tension of the string at B is made up of the centrifugal force at B together with the weight of the body;
 \therefore tension of string at B : weight of body, $\therefore 6 : 1$.

21. *If a body suspended by a string oscillate through a quadrant (the extremity of the quadrant being the lowest point); to compare the tension of the string with the weight of the body in any point of the descent.*

Let P (Fig. 80) be any point of the descent, W = whole weight of the body, w = that part of it which is employed in stretching the string, C = centrifugal force of the body at P, and $x = \sin. \angle PAB$ to

radius 1. Then gravity or weight of the body = g ,

$\therefore w = g x$; also centrifugal force = $\frac{V^2}{r} = 2 g x$; \therefore

$C + w =$ tension at $P = 3 g x$,

\therefore tension : weight :: $3 g x : g :: 3 x : 1$.

Cor. Hence the tension of the string at the lowest point = three times the weight of the body.

22. *Required the same in the cycloid.*

Let gravity or the weight of the body be represented by g , and put $D G$ (*Fig. 81*) = a , and $D F = x$; then

$g : w :: D G : D E :: D G^{\frac{1}{2}} : D F^{\frac{1}{2}} :: a^{\frac{1}{2}} : x^{\frac{1}{2}}$,

$\therefore w = \frac{g x^{\frac{1}{2}}}{a^{\frac{1}{2}}}$; also C upon the same scale = $\frac{V^2}{\frac{1}{2} P V}$

$$= \frac{2 g x}{2 x} = g;$$

$\therefore C + w$ or tension at $P = \frac{g x^{\frac{1}{2}}}{a^{\frac{1}{2}}} + g$

$$= g \times \frac{a^{\frac{1}{2}} + x^{\frac{1}{2}}}{a^{\frac{1}{2}}};$$

\therefore tension at P : weight :: $g \cdot \frac{a^{\frac{1}{2}} + x^{\frac{1}{2}}}{a^{\frac{1}{2}}} : g :: a^{\frac{1}{2}} + x^{\frac{1}{2}}$

: $a^{\frac{1}{2}}$.

Cor. At the lowest point, tension : weight :: 2 : 1.

23. *Let A P (Fig. 82) be a slender rod in the form of a curve, whose axis N A is perpendicular to the horizon, and let a ring be put upon it at any point P; suppose the rod to revolve about A N with such a velocity that the ring may remain at rest at P; required the nature of the curve A P,*

that the ring may also remain at rest at every other point of the rod.

Draw PT a tangent to the curve at P , put $NP = y$, $TN =$ subtangent $= t$, $V =$ velocity of the rod at P ; then if gravity be represented by g , we have centrifugal force at $P = \frac{V^2}{y} =$ suppose to PD ;

$\therefore \frac{V^2}{y} : \text{that part of the force which urges the body up the rod, or } PE :: PT : y,$

$$\therefore PE = \frac{V^2}{PT};$$

again, $grav^y$ or $g (= PC) : \text{that part of it which urges the body down the rod, or } PB :: PT : t;$

$$\therefore PB = \frac{gt}{PT};$$

but since the body remains at rest, $PE = PB$, *i. e.*

$$\frac{V^2}{PT} = \frac{gt}{PT}, \text{ and } V = \sqrt{g \times TN};$$

in like manner if p be any other point, the velocity necessary to make the ring rest at $p = \sqrt{g \times tn}$; \therefore in order that the body may remain at rest both at P and p ,

vel^y at P must be to vel^y at $p :: \sqrt{TN} : \sqrt{tn}$;

but vel^y at $P : vel^y$ at $p :: PN : pn$;

\therefore in order that the body may remain at rest both at P and p ,

TN must be to $tn :: PN^2 : pn^2$,

or the subtangent must be as the square of the ordinate, *i. e.* the curve must be a parabola.

Cor. Hence if a vessel of water revolve about its axis, the cavity formed in the fluid by the revolution of the vessel will be a paraboloid; for every particle of the water forming the surface of the cavity re-

mains at rest by the supposition, and \therefore by the foregoing Prob. must lie in the surface of the paraboloid.

24. *The curve A B P being a parabola, and the rest as before ; let it be required to find the proper velocity with which any point P must revolve, that the ring placed at P may remain at rest.*

Let x = space fallen through by gravity to acquire the required velocity ; then as before we have

$$P E = \frac{V^2}{P T} = \frac{2 g x}{P T},$$

$$\text{and } P B = \frac{g \times T N}{P T} = \frac{g \times 2 A N}{P T},$$

$\therefore \frac{2 g x}{P T} = \frac{2 g \times A N}{P T}$, $\therefore x = A N$, or the body must fall through a space equal to the abscissa of the curve.

Cor. If A P be any other curve, $x = \frac{T N}{2}$; or the space fallen through must = $\frac{1}{2}$ the subtangent.

25. *A cylindrical vessel is filled with water ; with what velocity must it be whirled round its axis that $\frac{1}{2}$ the water may be thrown out ?*

By Cor. Prob. 23, when the cylinder is turned round, the surface of the water in the vessel is a paraboloid ; and since the cylinder is full at first, the quantity of water thrown out will always be equal to the content of the paraboloid thus formed : now the greater the velocity of the cylinder, the greater will be the quantity of water thrown out ; *i. e.* the lower will the vertex descend ; and since by the Prob. just half the water is thrown out, the cylinder must be whirled with such a velocity that the vertex of the paraboloid may descend till it just touch the bottom of the cylin-

der ; for in that case the quantity of water thrown out = the content of the paraboloid inscribed in the cylinder = $\frac{1}{2}$ content of the cylinder. Let F A M (Fig. 83) be the surface of the water ; then since after it has assumed this position it is supposed to remain at rest, any particle as P is at rest. Let x = space fallen through to acquire the velocity of rotation at P ; then by proceeding as in last Prob., x = A N ; and for the same reason the velocity of a particle at M, or the velocity of the cylinder = velocity acquired down G A or the height of the vessel.

26. *A cylindrical vessel of a given magnitude is filled with water ; with what velocity must it be whirled round its axis, that the water may just cover $\frac{1}{2}$ the base ?*

Let A B C D (Fig. 84) be the cylinder, A m n B the cavity formed in the water, let the paraboloid A m L B be completed, and put H L = x , H G = h , then

$$A B^2 : m n^2 :: L H : L G :: x : x - h ;$$

$$\text{but by Prob. } A B^2 : m n^2 :: 2 : 1 ;$$

$$\therefore 2 : 1 :: x : x - h,$$

$$\text{and } 2 : 2 - 1 (1) :: x : h,$$

$\therefore x = 2 h$; hence by proceeding as in the last Prob. we shall have the velocity of a particle remaining at rest at B, or the velocity of the cylinder = that acquired in falling down H L or $2 h$.

27. *A frustum of a cone of given dimensions, and having its smaller end downwards, is filled with water ; with what velocity must it revolve round its axis, that all the water may be expelled ?*

Let A M N B (Fig. 84) be the frustum ; then in order that all the water may fly out, the velocity of the vessel must be such that the fluid would, if permitted, form itself into the paraboloid A B N L M

circumscribing the frustum; put $AB = a$, $MN = b$, $LH = x$, and $HO = h$; then

$$a^2 : b^2 :: x : x - h, \text{ and } a^2 : a^2 - b^2 :: x : h,$$

$\therefore x = \frac{a^2 h}{a^2 - b^2} = \text{space fallen through to acquire the velocity sought.}$

28. *Centrifugal force at the equator, arising from the earth's rotation round its axis: the centrifugal force in any parallel of latitude :: $\text{rad.}^2 : \cos. \text{latitude}^2$; supposing the earth a perfect sphere.*

Let Pp (Fig. 76) be the earth's axis, $\mathcal{A}E$ Q the equator, AB any parallel of latitude, $\lambda = \text{latitude}$, and take QD and Bn proportional to the centrifugal forces at Q and B ; resolve Bn into Bm and mn , then will Bm represent that part of the centrifugal force at B which diminishes the force of gravity;

then since $F \propto \frac{R}{P^2} \propto$ (since P is here given) R ,

we have

$$QD : Bn :: CQ : AB :: 1 : \cos. \lambda$$

$$\text{And } Bn : Bm :: CB : AB :: 1 : \cos. \lambda$$

$$\therefore QD : Bm :: 1^2 : \cos. \lambda^2.$$

Cor. 1. Hence, since QD is constant, the diminution of gravity, or that part of the centrifugal force which diminishes gravity, in going from pole to equator, $\propto \cos. \lambda^2$.

Cor. 2. Required the latitude in which centrifugal force = $\frac{1}{m}$ the centrifugal force at the equator.

$$\text{Here } 1^2 : \cos. \lambda^2 :: m : 1, \therefore \cos. \lambda = \frac{1}{\sqrt{m}}.$$

29. *Required the velocity of the earth round its axis, that the centrifugal force in lat. 60° may = force of gravity there.*

Let V = required velocity, C = centripetal force or gravity, c = centrifugal force at equator, $c' = \frac{V^2}{R}$ centrifugal force in latitude 60° ; then since $F \propto \frac{V^2}{R}$ we have

$$C : c :: g r : V^2$$

$$\text{but } c : c' :: 1^2 : \cos. \lambda^2 :: 4 : 1,$$

$$\therefore C : c' :: 4 g r : V^2;$$

$$\text{but } C = c' \text{ by hypothesis, } \therefore V = \sqrt{4 g r}.$$

30. *Required to find how the weight of the same body varies on different parts of the earth's surface.*

Let P = time of the earth's rotation round its axis; p = periodic time of a body revolving at the earth's surface; C = centripetal force or force of gravity; c = centrifugal force at the equator; c' = centrifugal force in any other parallel of latitude; then

$$C : c :: \frac{1}{p^2} : \frac{1}{P^2} :: P^2 : p^2$$

$$\& c : c' :: 1^2 : \cos. \lambda^2$$

$$\therefore C : c' :: P^2 : p^2 \cos. \lambda^2,$$

$$\& C : C - c' \text{ (or comparative weight)} :: P^2 : P^2 - p^2 \cos. \lambda^2;$$

but the 1st and 3d terms are constant,

$$\therefore \text{weight} \propto P^2 - p^2 \cos. \lambda^2.$$

Or thus. Let r = radius of the earth, v = velo-

city round its axis, then since $F \propto V^2$ when R is given,

$$\begin{aligned} C : c &:: V^2 : v^2 :: g r : v^2 \\ &\& c : c' :: 1^2 : \overline{\cos. \lambda}^2 \\ \therefore C : c' &:: g r : v^2 \cdot \overline{\cos. \lambda}^2 \\ \& C : C - c' &(\text{or comparative weight}) :: g r \\ &: g r - v^2 \cdot \overline{\cos. \lambda}^2 \\ \therefore \text{weight} &\propto g r - v^2 \cdot \overline{\cos. \lambda}^2. \end{aligned}$$

Cor. To compare the force of gravity in any two latitudes.

Let $L = \cos. \text{lat.}$ in one of the places, $l = \text{do.}$ at the other; then since force of gravity $\propto g r - v^2 \cdot \overline{\cos. \lambda}^2$, gravity at one place : gravity at the other $:: g r - L^2 v^2 : g r - l^2 v^2$ or $:: P^2 - p^2 L^2 : P^2 - p^2 l^2$.

31. *Required the Ratio of the times of oscillation of a pendulum in any two given latitudes, supposing the earth a sphere.*

Let L and l be the cosines of the two latitudes, T and t the times of oscillation of the pendulum at those latitudes, P and p as in the last Prob.; then since

time of oscillation $\propto \frac{1}{\sqrt{F^{\text{ce}}}}$, when the length of the pendulum is given, we have by Cor. Prob. 30,

$$T : t :: \sqrt{P^2 - p^2 L^2} : \sqrt{P^2 - p^2 l^2}.$$

Cor. If the two places be the pole and the equator, we have $l = \cos. 0 = \text{rad.}$, and $L = \cos. 90^\circ = 0$;

$$\therefore T : t :: \sqrt{P^2 - p^2} : P.$$

32. *In a given latitude a pendulum will oscillate once in a second, supposing the earth not to revolve round its axis; required the \angle^r motion round its axis, that the pendulum may oscillate once in two seconds.*

Let $v =$ required velocity round its axis; $l = \cos.$

latitude; F = force of gravity at 1st, or when the earth is at rest; f = force of gravity when it revolves round its axis; then since time of oscillation $\propto \frac{1}{\sqrt{F}}$, when the length of the pendulum is given,

$$\begin{aligned} 1 : 2 &:: \frac{1}{\sqrt{F}} : \frac{1}{\sqrt{f}} :: \sqrt{f} : \sqrt{F} \\ &:: \sqrt{gr - l^2 v^2} : \sqrt{gr} \text{ (by Cor. Prob. 30);} \\ &\therefore gr = 4gr - 4l^2 v^2, \\ &\& v^2 = \frac{3gr}{4l^2}, \text{ and } v = \frac{\sqrt{3gr}}{2l}. \end{aligned}$$

33. *Supposing a pendulum in latitude 60° to oscillate seconds, when the earth revolves round its axis with a velocity of v feet per second; required the velocity of the earth round its axis, that the pendulum may oscillate once in two seconds.*

Let V = required velocity, then, as before, comparative gravity $\propto gr - v^2 \cdot \cos^2 \lambda^2 \propto$ (in this case where latitude = 60° .) $4gr - v^2$,

$$\begin{aligned} \therefore 1 : 2 &:: \frac{1}{\sqrt{F}} : \frac{1}{\sqrt{f}} :: \sqrt{f} : \sqrt{F} \\ &:: \sqrt{4gr - V^2} : \sqrt{4gr - v^2}; \\ \therefore 4gr - v^2 &= 16gr - 4V^2, \\ \text{and } V &= \sqrt{\frac{12gr + v^2}{4}}. \end{aligned}$$

34. *A pendulum, vibrating in a certain time at the pole of the earth, vibrates once less in n times when carried to a place 30° from the equator. In what time does the earth revolve round its axis?*

N° of vibrations when length is given $\propto \sqrt{F}$, \therefore

$$n : n - 1 :: \sqrt{g r} : \sqrt{g r - \frac{3 v^2}{4}},$$

$$\therefore \text{by reduction } v = \sqrt{\frac{2 n - 1}{3 n^2}} \times \sqrt{4 g r}.$$

35. *Suppose the earth a sphere, and that a pendulum whose length is (a) inches vibrates seconds in latitude 60° . What will be the length of a pendulum that vibrates seconds at the equator?*

Here $L \propto F$ when time is given,

$$\therefore a : L :: P^2 - \frac{p^2}{4} : P^2 - p^2,$$

$$\therefore L = a \times \frac{4 P^2 - 4 p^2}{4 P^2 - p^2}.$$

36. *Compare the space described in $1''$ by gravity in any given latitude with that which would be described in the same time, if the earth did not revolve round its axis.*

This in other words is to compare space described in any latitude in $1''$ with that described in the same time at the pole.

Here $S \propto F$, \therefore

$$\text{S. in given latitude : S. at pole} :: P^2 - p^2 L^2 : P^2.$$

Cor. If the latter place were the equator we should have

$$\text{S. in given latitude : S. at equator} :: P^2 - p^2 L^2 : P^2 - p^2.$$

37. Let the Force act in the direction of the ordinates ; to find the curve when $F \propto \frac{1}{y^2}$.

$$F \propto -\frac{d^2y}{dx^2} \propto \frac{1}{y^2}, \therefore -d^2y \propto \frac{dx^2}{y^2},$$

$$\text{and } -dy \, d^2y \propto \frac{dy \, dx^2}{y^2}, \therefore -\frac{dy^2}{2} \propto -\frac{dx^2}{y},$$

$$\therefore dy \sqrt{y} \propto dx, \text{ and } x \propto y^{\frac{3}{2}},$$

or the curve is the semicubical parabola.

38. Required the curve in which a body, revolving by a force which acts in lines \perp^r to the axis, shall approach or leave the axis with a velocity always proportional to the ordinate.

$$\text{Here } v \propto y \text{ or } dy \propto y, \therefore \frac{dy}{y} \text{ is constant, or } \frac{dy}{y} \propto dx,$$

and if M be a proper constant Q^y , $M \cdot \frac{dy}{y} = dx$,
which is the property of the logarithmic curve.

39. Compare the velocity at any point in a curve with that in a \odot at the same distance when the \angle formed by the distance and tangent is a minimum. (Fig. 8.)

$$\text{Sin. } \angle SPY = \frac{p}{y} = \text{min.} \therefore \frac{y \, dp - p \, dy}{y^2} = 0,$$

$$\therefore \frac{p \, dy}{dp} = \frac{1}{2} \text{ ch. curvature} = y, \therefore$$

$$V : \text{vel. in } \odot :: \sqrt{y} : \sqrt{y} :: 1 : 1.$$

40. If the force vary according to any law of the dis-

tance ; shew that in any orbit, at the point where the centripetal and centrifugal forces are equal, the velocity towards the centre of force is a maximum.

By Art. 103, paracentric velocity $\propto \frac{\sqrt{y^2 - p^2}}{py}$

& \therefore when a maximum $\frac{1}{p^2} - \frac{1}{y^2} = \text{max.}$

$$\therefore \frac{2 dp}{p^3} = \frac{2 dy}{y^3} \text{ \& } 2 y^3 = \frac{2 p^3 dy}{dp} = p^2 \cdot \frac{2 p dy}{dp},$$

or $2 SP^3 = SY^2 \cdot PV$, \therefore centrip. = centrif. force.

41. *Find in what curve a body must revolve round a repulsive force, varying as the distance from a point, so that its velocity may always equal that in a \odot at the same distance round an equal attractive centre of force.*

It is evident the curve must be an hyperbola, the centre of force in the centre; and it may be proved, as in Art. 135, that

the velocity in this curve : velocity in \odot at the same distance round an equal attractive force
 $\therefore CD : CP,$

\therefore by Prob. CD always $= CP$, which is the property of the equilateral hyperbola;

the body \therefore moves in this curve.

42. *How must the force be changed in an ellipse, to make a body move in a parabola?*

$$F \propto \frac{V^2}{P V} \propto (\text{in this case where } V \text{ is given}) \frac{1}{P V};$$

$$\therefore F \text{ in ellipse} : F \text{ in parabola} :: 4 SP : \frac{2 SP \cdot PH}{AC}$$

$$:: 2 AC : PH.$$

43. *How must the force be changed in an ellipse at the lower apse, that the body may describe a circle?*

As in the last $F \propto \frac{1}{PV}$, \therefore

$$F \text{ in ell.} : F \text{ in } \odot :: 2 \text{ distance} : \frac{2 CB^2}{AC} :: \text{distance} : \frac{1}{2} \text{ lat. rect.}$$

44. *Compare the velocity of a body at the extremity of the latus rectum of an ellipse with the velocity at the mean distance; force being in the focus.*

$$V^2 \propto \frac{1}{SY^2} \therefore$$

$$V^2 \text{ at extremity of L. R.} : V^2 \text{ at m. distance} :: CB^2 : SY^2$$

$$:: CB^2 : CB^2 \frac{SP}{PH} :: HP : SP$$

$$:: 2AC - \frac{L}{2} : \frac{L}{2} :: 2AC^2 - CB^2 : CB^2$$

$$:: 1 + e^2 : 1 - e^2, \text{ where } e = \text{excentricity} = \frac{SC}{AC}$$

45. *A comet is in the perihelion of a given ellipse; compare its velocity with the velocity it would have in a parabola at the same perihelion distance.—(Fig. 14.)*

$$V^2 \propto PV \text{ when } F \text{ is given,}$$

$$\therefore V^2 \text{ in ell.} : V^2 \text{ in parab.} :: \frac{2CB^2}{AC} : 4MS$$

$$:: AS : 2AC :: 1 + e : 2.$$

46. *If a body move in a conic section (force tending to*

focus); the velocity at the distance SP is to the velocity at any other distance SQ as a mean proportional between HP, and SQ is to a mean proportional between SP and HQ.

$$V^2 \propto \frac{1}{SY^2} \text{ or } \propto PV, \therefore$$

$$\begin{aligned} V. \text{ at } P : V. \text{ at } Q &:: CB. \sqrt{\frac{SQ}{QH}} : CB. \sqrt{\frac{SP}{PH}} \\ &:: \sqrt{SQ.PH} : \sqrt{SP.QH} \end{aligned}$$

47. If a body revolve in an ellipse (whose major and minor axes are given) with the force tending to the focus, and the time of revolution be given; find the actual velocity of the body at any given point in its orbit.

Let t = per. time = P. T. in \odot rad. AC, a = $\frac{1}{2}$ ax. maj. d = any distance; then velocity at the mean distance = velocity in \odot radius AC = $\frac{2\pi a}{t}$,

$$\therefore \text{ since } V^2 \propto \frac{1}{SY^2},$$

$$\frac{2\pi a}{t} : V \text{ at distance } d :: \sqrt{\frac{d}{2a-d}} : 1,$$

$$\therefore V = \frac{2\pi a}{t} \times \sqrt{\frac{2a-d}{d}}.$$

48. Determine the \angle distance of a body from the vertex of an ellipse, whose eccentricity = $\frac{1}{2}$; at which the velocity : greatest velocity :: 1 : $\sqrt{3}$ — (Fig. 14.)

$$\text{Since } V^2 \propto \frac{1}{SY^2},$$

$$1 : 3 :: SM^2 : CB^2. \frac{SP}{PH} :: \frac{1}{4} : \frac{3}{4}. \frac{SP}{PH}$$

$\therefore SP = PH$, or the body is at B;

to find $\angle BSM$ we have $SC = \frac{1}{2}$, and $CB = \frac{\sqrt{3}}{2}$,

$\therefore BSC = 60^\circ$. and $BSM = 120^\circ$.

49. *Given the velocity of projection = to the velocity in a circle at the same distance ($F \propto \frac{1}{D^2}$); required the direction in which a body must be projected at a given distance, that the focus of the conic section described may bisect the $\frac{1}{2}$ ax. maj. : and determine the magnitude and position of the axes.—(Fig. 14.)*

The point of projection must be the extremity of the $\frac{1}{2}$ axis minor, and the given distance = $SB = AC =$ (by Prob.) $2SC$; also if a tangent be supposed drawn at B, the \angle it makes with $SB = \angle$ of projection = BSC ; to find which we have

$$SB : SC :: 2 : 1 :: 1 : \cos. BSC = \frac{1}{2},$$

$\therefore \angle$ of projection = 60° . Hence $\frac{1}{2}$ ax. maj. = the given distance, and makes with it an \angle of 60° ;

$$\text{also } BC = \sqrt{SB^2 - SC^2} = AC \cdot \frac{\sqrt{3}}{2}.$$

50. *The times of moving from the perihelion to the extremity of the lat. rect. in different parabolas vary in the sesquiplicate ratio of the perihelion distances.*

$$\text{For } P.T. \propto \frac{A}{a} \propto \frac{A}{\sqrt{L}} \propto \frac{\frac{1}{2}L^2}{\sqrt{L}} \propto L^{\frac{3}{2}}.$$

51. *Having given the major and minor axes of an ellipse, and the force in the focus; compare the P. T. in the ellipse with the P. T. in a \odot , whose radius = greatest distance in the ellipse.—(Fig. 14.)*

P. T. in an ellipse or P. T. in \odot rad. SB :

$$\begin{aligned} \text{P. T. in } \odot \text{ rad. } S A &:: S B^{\frac{1}{2}} : S A^{\frac{1}{2}} \\ \therefore a^{\frac{3}{2}} : a + \sqrt{a^2 - b^2}^{\frac{3}{2}} &\text{ or } :: 1 : 1 + e^{\frac{1}{2}}. \end{aligned}$$

52. *Given the velocity at any point of an ellipse (force in the focus) ; it is required to find the per. time.*

Let v = velocity at the given distance d ; then
 v : velocity at mean distance or velocity in \odot at mean

$$\text{distance} :: 1 : \sqrt{\frac{d}{2a-d}},$$

$$\therefore \text{velocity in } \odot \text{ at m. distance} = v \sqrt{\frac{d}{2a-d}},$$

$$\begin{aligned} \therefore \text{P. T. in } \odot \text{ at mean distance} &= \text{P. T. in ellipse} \\ &= \frac{\text{circ.}}{V} = \frac{2\pi a}{v} \cdot \sqrt{\frac{2a-d}{d}}. \end{aligned}$$

53. *Compare the time of a revolution about the centre of a given ellipse with that about its focus.*

$$\text{By Art. 137, P. T. round centre} = \frac{2\pi}{\sqrt{\phi}},$$

$$\text{and by Art. 145, P. T. round focus} = \frac{2\pi a^{\frac{3}{2}}}{\sqrt{\phi}} ;$$

$$\therefore P : p :: 1 : a^{\frac{3}{2}}.$$

54. *Find the actual P. T. in a given ellipse (centre of force in the focus) ; supposing the force at a given distance (d) is to the force of gravity as $F : 1$.*

Force at distance $d = g F$, & \therefore at mean distance

$$= g F \cdot \frac{d^2}{a^2}$$

∴ P. T. in ☉ at mean distance or P. T. in ellipse

$$= \frac{\pi}{d} \sqrt{\frac{4a^3}{gF}}.$$

55. *If an n^{th} part of the earth were taken away, what change would be produced in the moon's orbit, and in what ratio would her periodic time be increased, the moon's orbit before the change being supposed circular?*

Since $F \propto \frac{1}{D^2}$, the new orbit will be one of the conic sections, the centre of the earth being in the focus. Let ∴ A P Q (*Fig. 75*) be the original, and A R M the new orbit, and let the change take place when the body is at A; then since the original orbit is a ☉, the point A will be an apse of the conic section A R M.

$$\text{Now } F \propto \frac{V^2}{P V} \propto (\text{in this case}) \frac{1}{P V};$$

∴ force before change or (1) : force after ($1 - \frac{1}{n}$)

$$\therefore \frac{2CD^2}{AC} : 2SA,$$

$$i. e. n : n - 1 :: \frac{2CD^2}{AC} : 2SA :: \frac{2SA \cdot SM}{AC} : 2SA$$

$$\therefore SM : AC :: 2AC - AS : AC;$$

$$\therefore AC = \frac{n-1}{n-2} \cdot SA.$$

Now (1) let $n = 2$, *i. e.* let $\frac{1}{2}$ the earth be taken away, then will AC be infinite, or the curve in that case will be a parabola.

(2) Let n be less than 2, *i. e.* let more than $\frac{1}{2}$ the earth be taken away, then will AC be finite but negative; ∴ curve is an hyperbola.

(3) Let n be greater than 2, or let less than $\frac{1}{2}$ the

earth be taken away; then will AC be finite and positive, or the curve in that case will be an ellipse, whose $\frac{1}{2}$ axis major $= \frac{n-1}{n-2} \cdot SA$.

To find the change in the periodic time; we have

$$P \propto \frac{\left(\frac{1}{2} \text{ ax. maj.}\right)^{\frac{3}{2}}}{\rho^{\frac{1}{2}}},$$

$$\therefore \text{P. T. before change} : \text{P. T. after} :: \frac{SA^{\frac{3}{2}}}{1}$$

$$: \frac{\left(\frac{n-1}{n-2} \cdot SA\right)^{\frac{3}{2}}}{\left(\frac{n-1}{n}\right)^{\frac{1}{2}}} :: n-2 : n^{\frac{1}{2}} n-1;$$

which R° is only real and finite when n is greater than 2, or when the curve is an ellipse.

$$\begin{aligned} \text{Cor. In the two last cases } \left(\frac{1}{2} \text{ ax. min.}\right)^2 &= AS \cdot SM \\ &= AS \cdot AM - AS^2 = \frac{n}{n-2} \cdot SA^2. \end{aligned}$$

56. *Supposing the velocity with which a body would revolve in a circle at the earth's surface to be given; what must be the velocity, the direction continuing the same, that the excentricity of the orbit may be 1000 miles?*

Let APQ (former figure) be a great \odot of the earth, ARM the ellipse described by the body, S the centre of the earth or focus of the ellipse, SC the excentricity; put $AS = r$, $SC = a$, $V =$ velocity in ARM at A , $v =$ velocity in APQ at A ;

then since $F \propto \frac{V^2}{P \cdot V}$ and that F is the same at A in both cases,

$V^2 \propto P V$; hence

$$\begin{aligned} V^2 : v^2 &:: \frac{2 C D^2}{A C} : 2 S A :: \frac{2 S A \cdot S M}{A C} : 2 S A \\ &:: S M : A C :: 2 a + r : a + r, \\ \therefore V &= v \sqrt{\frac{2 a + r}{a + r}}. \end{aligned}$$

Cor. If a be infinitely greater than r , or the path of the body be a parabola $V = v \sqrt{2}$.

57. *The velocity in an ellipse at the greatest distance is half that with which a body would move in a parabola at the same distance; what is the eccentricity of the ellipse?—* (Fig. 14.)

$$\begin{aligned} V^2 &\propto P V, \therefore \\ 1 : 4 &:: \frac{2 C B^2}{A C} : 4 S A :: \frac{C B^2}{S A} (S M) : 2 A C, \\ \therefore S C &= \frac{A C}{2}; \text{ and } \frac{S C}{A C} \text{ or } e = \frac{1}{2}. \end{aligned}$$

58. *Suppose a comet in its descent towards the sun to impel the earth from a circular orbit in a direction making any acute \angle with the earth's distance; and the velocity after impact : velocity before :: $\sqrt{3} : \sqrt{2}$; find what change would be produced in the length of the year.*

$$\begin{aligned} 3 : 2 &:: H P : A C :: 2 A C - r : A C, \\ \therefore A C &= 2 r, \\ \therefore P T. \text{ before impact} : P. T. \text{ after} &:: r^{\frac{3}{2}} : 2 r^{\frac{3}{2}} \\ &:: 1 : 2 \sqrt{2}. \end{aligned}$$

59. *If with a force varying as $\frac{1}{D^2}$, a velocity which is to the velocity in a \odot :: $\sqrt{3} : \sqrt{2}$, at an $\angle S$, and at a*

distance d , a body be projected; find the excentricity of the orbit described.

As before, $A C = 2 d$.

Again, $p : d :: \sin. \vartheta : 1$

$$\begin{aligned} \therefore p &= d \cdot \sin. \vartheta, \text{ but } p^2 = b^2 \frac{S P}{2 A C - S P} \\ &= b^2 \frac{d}{3 d} = \frac{b^2}{3}, \\ \therefore b^2 &= 3 p^2 = 3 d^2 \sin^2 \vartheta, \therefore S C = \sqrt{a^2 - b^2} \\ &= \sqrt{4 d^2 - 3 d^2 \sin^2 \vartheta} \\ \text{and } \frac{S C}{A C} \text{ or } e &= \sqrt{1 - \frac{3}{4} \sin^2 \vartheta}. \end{aligned}$$

60. Force varying as $\frac{1}{D^2}$, a body is projected from a given point in a direction which makes an \angle of 60° with the distance, with a velocity which is to the velocity in a parabola as $1 : \sqrt{3}$. Find the major axis, the position of the apse, and the excentricity of the ellipse described.—(Fig. 14.)

$$V^2 \propto P V, \therefore 1 : 3 :: 2 A C - S P : 2 A C,$$

$$\therefore A C = \frac{3 S P}{4} \text{ and } P H = \frac{S P}{2}.$$

$$\text{Again, } S P : S Y :: 1 : \sin. 60 :: 2 : \sqrt{3},$$

$$\begin{aligned} \therefore S Y^2 &= \frac{3 S P^2}{4}, \text{ and } P Y^2 = \frac{S P^2}{4} \text{ \& } P Y = \frac{S P}{2} \\ &= P H, \therefore \triangle^s S P H \text{ \& } S P Y \text{ are similar and equal.} \end{aligned}$$

Hence $\angle P S A = 30^\circ$ and $P S M = 150^\circ$
= position of the apse.

$$\text{Lastly, } S H = S Y \text{ \& } S C = \frac{S Y}{2} = \frac{S P \sqrt{3}}{4},$$

$$\therefore \frac{SC}{AC} \text{ or } e = \frac{1}{\sqrt{3}}.$$

61. *Given the major and minor axes of an ellipse : required the radius of a \odot described round the focus as a centre, in which the periodic time is equal to the time of moving through the aphelion, from mean distance to mean distance.—(Fig. 14.)*

Let P = periodic time in required \odot . rad. x ; p = time from mean distance to mean distance;

then since $P. T. \propto \frac{A}{\sqrt{L}}$ we have

$$P : p :: \frac{\pi x^2}{\sqrt{2} x} : \frac{\frac{1}{2} \text{ area of ell.} + 2 \triangle SCB}{\sqrt{L}}$$

$$:: \frac{\pi x^2}{\sqrt{2}} : \frac{\frac{\pi a b}{2} + b \sqrt{a^2 - b^2}}{\sqrt{\frac{2 b^2}{a}}} :: 2 \pi x^{\frac{3}{2}}$$

$$: \pi a^{\frac{3}{2}} + 2 a^{\frac{1}{2}} \sqrt{a^2 - b^2};$$

$$\text{but } P = p, \therefore x = \frac{\pi a^{\frac{3}{2}} + 2 a^{\frac{1}{2}} \sqrt{a^2 - b^2}}{\frac{2 \pi}{\sqrt{\frac{2 b^2}{a}}}}^{\frac{2}{3}},$$

$$\text{or, in terms of } e, = a \cdot \frac{\pi + 2 e}{2 \pi}^{\frac{2}{3}}.$$

62. *The perihelion distance of a comet is $\frac{1}{3}$ the distance of the earth from the sun, and its orbit which is parabolical, and the earth's which is circular, are in the same plane; how many days is the comet within the earth's orbit?*

Let PT_p be the earth's orbit (Fig. 69), then

$$\text{since } P. T. \propto \frac{A}{a},$$

P. T. of earth : T. through P A p

$$\therefore \frac{\odot P T p}{\sqrt{L}} : \frac{S P A p}{\sqrt{l}}.$$

Now to find parabolic area S P A p we have

$$S P = r = A N + A S = A N + \frac{r}{3},$$

$$\therefore A N = \frac{2r}{3}, \text{ and } A S = S N.$$

Again, $4 A S \cdot A N = P N^2$, $\therefore P p = 2 P N$

$$= \frac{4r}{3} \cdot \sqrt{2},$$

$$\text{hence area } P A p = \frac{2}{3} A N \cdot P p = \frac{16r^2}{27} \cdot \sqrt{2},$$

$$\text{and } \triangle P S p = P N \cdot S N = \frac{2r^2}{9} \cdot \sqrt{2},$$

$$\therefore S P A p = P A p - \triangle P S p = \frac{10r^2}{27} \sqrt{2}.$$

Also L. R. in \odot : L. R. in parab. $\therefore 2r : \frac{4r}{3} \therefore 3 : 2$,

\therefore P. T. of earth (365^d) : T through S P A p

$$\therefore \frac{\pi r^2}{\sqrt{3}} : \frac{10r^2}{27} \therefore 27\pi : 10\sqrt{3}.$$

63. Find the perihelion distance of the comet that stays the longest time within the earth's orbit.—(Fig. 69.)

$$\begin{aligned} S P A p &= \frac{2}{3} A N \cdot P p - \triangle P S p \\ &= \frac{4}{3} A N \cdot P N - S N \cdot P N \end{aligned}$$

$$\begin{aligned}
& \propto 4 \text{ AN} \cdot \text{PN} - 3 \text{ SN} \cdot \text{PN} \\
& \propto \text{PN} \times 4 \text{ AN} - 3 \text{ SN} \\
& \text{Put SP} = r, \text{ AS} = x, \therefore r = \text{AN} + x \text{ and} \\
& \quad \text{AN} = r - x, \\
& \therefore \text{SN} = r - 2x \text{ and } \text{PN} = \sqrt{4x \cdot \text{AN}} = \\
& \quad \sqrt{4x \cdot r - x}, \\
& \therefore \text{Area} \propto \sqrt{4x \cdot r - x} \times r + 2x, \\
& \therefore \text{by Prob. } \frac{\text{SPAP}}{\sqrt{\text{L}}} = \text{max. or } \frac{\sqrt{4x \cdot r - x} \cdot r + 2x}{\sqrt{x}} \\
& = \text{max. or } \sqrt{r - x \cdot r + 2x}^2 = \text{max.} \\
& \therefore \text{by reduction } x = \frac{r}{2}.
\end{aligned}$$

64. *Given the perihelion distance of a comet describing a parabola, and the radius of the earth's orbit here supposed circular; compare the time of the comet's moving through 90 degrees of true anomaly with the length of the solar year.*

Put SP = r, AS = a, then

$$\begin{aligned}
\text{P. T. of earth : T. through } 90^\circ & :: \frac{\pi r^2}{\sqrt{2r}} : \frac{\frac{3}{2}a \cdot 2a}{\sqrt{4a}} \\
& :: \frac{\pi r^{\frac{3}{2}}}{\sqrt{2}} : \frac{2a^{\frac{3}{2}}}{3}
\end{aligned}$$

65. *An imperfectly elastic body revolving in an ellipse, whose excentricity is $\frac{1}{2}$, is reflected at the mean distance by a plane coincident with the distance so as to move after impact in the direction of the axis minor; find the degree of elasticity, and compare the periodic times in the two ellipses.— (Fig. 14.)*

In $\triangle \text{SBC}$ since SC = $\frac{1}{2}$ and SB = 1, $\angle \text{BSC}$

$= 60^\circ = \angle$ of incidence which the direction of the body makes with the plane, and \therefore the \angle of reflexion which the direction of the body makes after impact with the same plane produced $= 30^\circ$, \therefore by mechanics,

Velocity before imp. : velocity after $:: \sin. 60^\circ :$

$$\sin. 30^\circ :: \sqrt{3} : 1;$$

but $V^2 \propto P V$

\therefore ch. cur. before impact. : ch. cur. after $:: 3 : 1$,

or if $x = \frac{1}{2}$ ax. maj. of new orbit,

and $a = S B = A C$,

$$\frac{2 a^2}{a} : \frac{2 a \cdot 2 x - a}{x} :: 3 : 1,$$

$$\therefore x = \frac{3 a}{5} \therefore$$

$$P. T. \text{ before} : P. T. \text{ after} :: a^{\frac{3}{2}} : \left(\frac{3 a}{5} \right)^{\frac{3}{2}} :: 5 \sqrt{5} : 3 \sqrt{3}.$$

Lastly by mechanics,

F^{ce} compression : F^{ce} of elasticity $::$

$$\tan. 60^\circ : \tan. 30^\circ :: 3 : 1.$$

66. Find the R^o of the velocity at the extremity of the latus rectum of an ellipse (the force being in the focus) to the velocity in a \odot whose radius is the distance of the nearer apside from the focus, and shew that as the excentricity is encreased, this R^o approaches to a R^o of equality.

$$V \propto \frac{\sqrt{L}}{S Y},$$

$\therefore V$. at extremity of L. R. : V . in \odot r . S M

$$(Fig. 14) :: \sqrt{2 A C^2 - C B^2} : \sqrt{A C \cdot S A}$$

$$\begin{aligned}
 &:: \sqrt{AC^2 + AC^2 - CB^2} : \sqrt{AC \cdot SC + CA} \\
 &:: \sqrt{AC^2 + SC^2} : \sqrt{AC^2 + AC \cdot SC} \\
 &:: \sqrt{1 + e^2} : \sqrt{1 + e}, \text{ where } e = \frac{SC}{AC} \\
 &= \text{excentricity.}
 \end{aligned}$$

This R° . decreases till $e = \sqrt{2} - 1$, it is then least, and thence approaches to 1.

67. *If a body revolve in an ellipse, the force being in one focus, the \angle^r . velocity about the other focus is not accurately equal to the mean \angle^r . velocity except at four points. Determine those points.*

By Art. 152, Ex. 5, we have

$$\angle^r. \text{ vel. round } S : \angle^r. \text{ vel. round } H :: \frac{1}{SP^2} : \frac{1}{CD^2}$$

and (Art. 152. Ex. 3) mean \angle^r . velocity round $S ::$

$$\frac{1}{AC \cdot CB} : \frac{1}{SP^2}$$

$$\therefore \text{mean } \angle^r. \text{ velocity} : \angle^r. \text{ velocity round } H ::$$

$$\frac{1}{AC \cdot CB} : \frac{1}{CD^2};$$

\therefore when \angle^r . velocity round $H =$ mean \angle^r . velocity,
 $CD^2 = AC \cdot CB$, or $SP \cdot PH = AC \cdot CB$,

$$\therefore x \cdot 2a - x = ab \text{ and } x = a + \sqrt{a^2 - ab}.$$

Or the four values of CD may be determined geometrically exactly as for CP in Art. 136; and if to these conjugate diameters be drawn, we shall have the required distances.

68. *The eccentricity of the earth's orbit being small, the variation of the \angle^r . velocity is nearly proportional to the cosine of the \angle made by the radius vector and the perihelion distance.*

Variation of \angle^r . velocity from mean \angle^r . velocity

$$\begin{aligned} & \propto \frac{1}{SP^2} - \frac{1}{ab} \\ & \propto \frac{1 + e \cos. v}{a^2 \cdot 1 - e^2} - \frac{1}{a^2 \cdot \sqrt{1 - e^2}} \\ & \propto (1 + 2 e \cos. v + \&c.) - (1 - \frac{3}{2} e^2 \&c.) \\ & \propto 2 e \cos. v + \&c. \propto \cos. v \text{ nearly.} \end{aligned}$$

69. *Shew the earth's \angle^r . velocity to be nearly twice as great as it would have been had the earth's motion been uniform.—(Fig. 14.)*

Let A and a = earth's \angle^r . velocity at M and A ;
A' and a' = D². supposing the motion had been uniform ; then since \angle^r . velocity $\propto \frac{1}{D^2}$ in the 1st case,

and $\propto \frac{1}{D}$ in the second,

$$A - a : a :: SA^2 - SM^2 : SM^2 :: 2 AC. 2 SC : SM^2$$

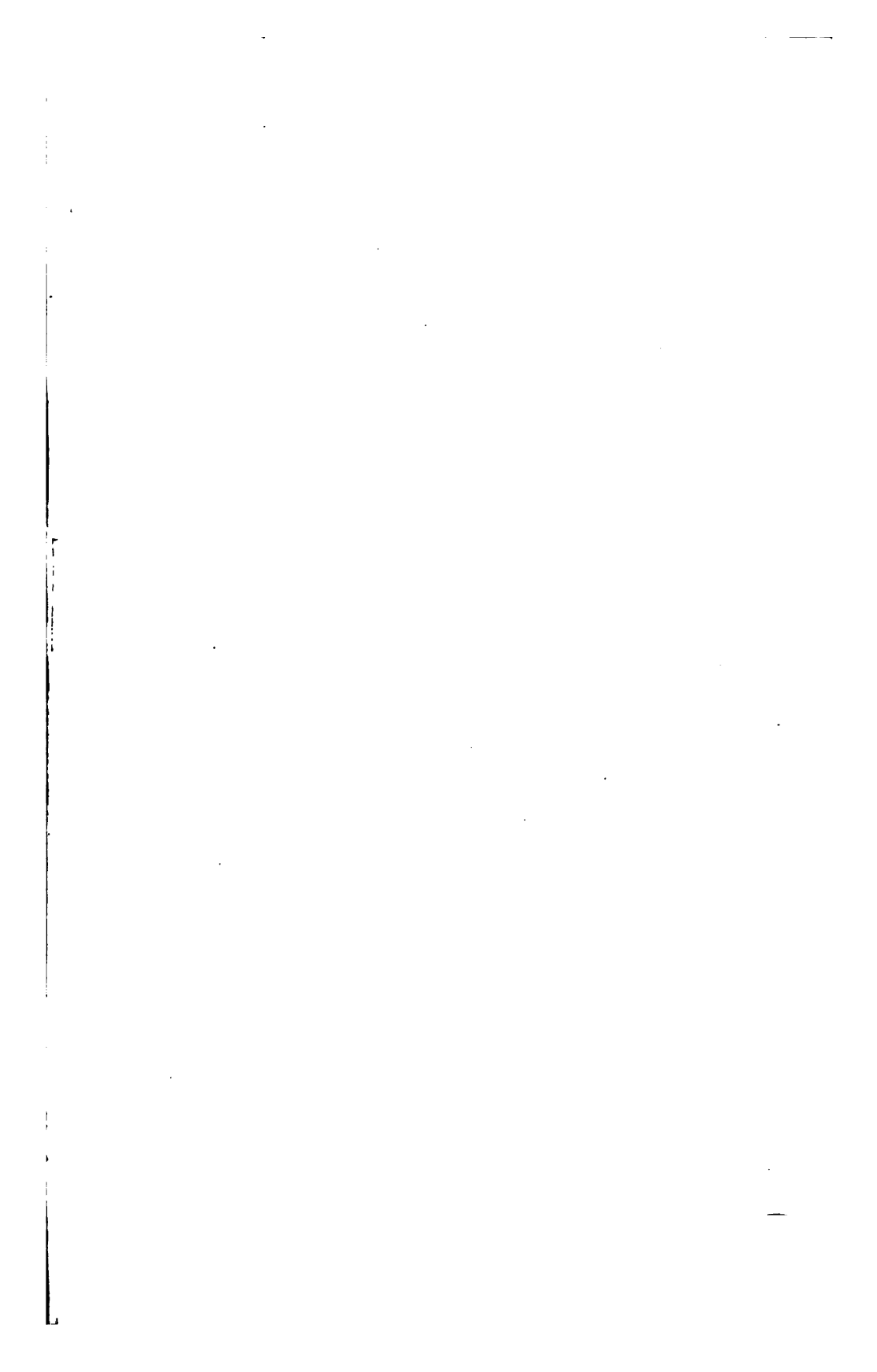
$$\text{and } a' : A' - a' :: SM : 2 SC ; \text{ but}$$

$$a : a' :: v^r \text{ at A} : \text{mean } v^r :: \frac{1}{SA} : \frac{1}{CB} :: CB : SA$$

$$\begin{aligned} \therefore A - a : A' - a' :: 2 AC. CB : SM. SA :: 2 AC \\ : CB :: 2 : \sqrt{1 - e^2} :: 2 : 1 \text{ nearly, since the ex-} \\ \text{centricity of the earth's orbit is small.} \end{aligned}$$

FINIS.

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